Report 346

The Paleozoic and Related Aquifers of Central Texas

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Texas Water Development Board

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The Paleozoic and Related Aquifers of Central Texas

by
Richard D. Preston, Geologist
Dianne J. Pavilcek, Geologist
Robert L. Bluntzer, Geologist
and
John Derton, Engineering Technician

Prepared by the Texas Water Development Board in cooperation with
The Lower Colorado River Authority,
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and The Hill Country Underground Water Conservation District

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ABSTRACT

The following summarizes a report resulting from an TWDB-LCRA cooperative ground-water study of the Paleozoic aquifers of central Texas. These consist of the Hickory, Ellenburger-San Saba, Marble Falls, and Mid-Cambrian aquifers. Around the edges of the study area and overlapping these older aquifers are the Edwards-Trinity (Plateau) and Trinity aquifers. These aquifers provide small to large amounts of water for most uses over much of the area. Locally, shallow alluvial aquifers and shallow weathered fracture zones in PreCambrian metamorphic and igneous rocks provide minor amounts of water for domestic and livestock supply.

Surface water is used for at least part of the municipal supplies of Llano, Burnet, and Marble Falls. Johnson City has used surface water in the past to supplement its ground-water supply. Surface water has also been used for electric power generation at Lake Buchanan, for a significant part of supplies for livestock, and a major part of irrigation supplies in Gillespie and San Saba counties. The municipal supply for the City of San Saba is obtained from San Saba Springs and shallow wells right at the springs, but is considered surface water by the TNRCC.

For the seven core counties (Blanco, Burnet, Gillespie, Llano, McCulloch, Mason, and San Saba) ground water supplied 65 percent of the total demand in 1980, 66 percent in 1985, 68 percent in 1990, and 73 percent in 1992.

The Board has estimated the annual availability of ground water from the Paleozoic aquifers at 46,149 acrefeet for the Hickory, 34,912 acrefeet from the Ellenburger-San Saba, 26,400 acrefeet for the Marble Falls, and 1,260 acrefeet for the Mid-Cambrian. These figures are the estimated average annual recharge for each of the aquifers. Since 1980, estimated total pumpage from the Hickory has ranged from 20,857 to 28,348 acrefeet, with an average of 26,351 acrefeet per year. Pumpage from the Ellenburger-San Saba varied from 4,638 to 13,609 acrefeet, with an average of 6,788 acrefeet. The Marble Falls pumpage ranged from 693 to 1,350 acrefeet, and averaged 929 acrefeet. Based on these estimates, there are obviously significant amounts of water available for future development from these aquifers in some areas. Additional ground-water pumpage will have some effects on spring flows and rejected recharge amounts which will effect baseflow in the surface water streams. Therefore, the location and amounts of additional withdrawals should be carefully studied and planned to minimize these effects.

The initial baseflow of the major streams within the area comes from seeps and springs in the Edwards-Trinity (Plateau) aquifer. Surface-water flow measurements show a complicated interaction between ground and surface water across the outcrops of the Paleozoic formations, with considerable gain and loss to the streams associated with the complex faulting of the area.

While relatively simplistic, smaller scaled computer flow models have been constructed for parts of the aquifers, a model of the entire extent or even any appreciable part of the Paleozoic aquifers would not be feasible as a management tool for these aquifers, at least at this time. The complex geologic structure, especially the extensive faulting which compartmentalizes the aquifers, along with the current lack of reliable data throughout much of the area would make it impossible to construct a model which would replicate the internal flow within this complicated system of aquifers and the surface streams and allow useful prediction of the result of possible future pumping.

The chemical quality of water from these aquifers is quite good over much of the area. The Hickory produces excellent water quality water down to depths in excess of 3,000 feet and the Ellenburger-San Saba down to depth of around 2,000 feet. The Marble Falls contains good quality water for some distance downdip, while the Mid-Cambrian produces good quality water on an immediately downdip from its outcrop.

There are some isolated water quality problems in water from wells in this area. Nitrate pollution of water occurs erratically in all of the aquifers. There are some incidents of naturally occurring high radioactivy in water from a few wells and springs producing from all of the Paleozoic aquifers, including gross alpha, gross beta, Radium-226, Radium-228, and radon gas.. This has included some samples from Brady's and San Saba's municipal supplies.

Several areas of relatively high concentration of pumpage for both irrigation and municipal demands has caused some amounts of water-level decline. Care in the location and construction of new and/or replacement wells will help to prevent additional water-level problems. In addition, aggressive programs of conservation should be implemented throughout the area. Both HUGWCD and the HCUWCD have conservation plans and have considered plans for recharge enhancement activities.

INTRODUCTION

Purpose and Scope

This report is the result of a cooperative Texas Water Development Board (Board) – Lower Colorado River Authority (Authority) – Hill Country Underground Water Conservation District (HCUGWCD) – Hickory Underground Water Conservation District (HUGWCD) ground-water study of Paleozoic aquifers of the central Texas region. It was initiated under a project description prepared by the Board and the Authority and agreed to by the Districts in September, 1992. The main purpose was to better delineate the area aquifers, and attempt to derive estimates of the amount of water available from the aquifers. A secondary purpose was to determine if a digital flow model of the aquifers or parts of the aquifers could be constructed which could be used as a management tool for planning future water development in the area.

The specific scope of the study included: review of existing data and reports, inventory and/or reinventory of existing high capacity wells and springs, collection of water samples from selected wells for chemical analysis, review of past pumpage and projected future demands, collection of winter low-flow measurements of major streams, evaluation and analysis of all data, and preparation of a report outlining the occurrence, availability, and quality of ground water within the Paleozoic and related aquifers of central Texas. A second volume of the report which contains tabulations of data collected for the study will be provided to the cooperators. This data will be available as an open-file report to all interested parties and copies of the data can be obtained in either hard copy or digital computer format from the Board at any time.

Location and Extent

The study area is located in central Texas, west of the city of Austin and northwest of San Antonio. It includes all or parts of Llano, Mason, San Saba, McCulloch, Gillespie, Kimble, Menard, Concho, Coleman, Brown, Mills, Lampasas, Blanco, Burnet, Williamson, and Travis counties (see Figure 1). This area includes the outcrop and downdip extent of the Paleozoic aquifers (Hickory, Mid-Cambrian, Ellenburger-San Saba, and Marble Falls aquifers). In places, these aquifers are overlain and possibly hydrologically connected with the Edwards-Trinity (Plateau) and Trinity aquifers of Cretaceous age and various discontinuous alluvial aquifers of Quaternary and Recent age. The study area includes approximately 5,500 square miles and is mostly within the drainage area of the Colorado River and its tributaries. The total extent of the early Paleozoic aquifers in central Texas, including the central area where granites, gneisses, and schists are exposed, is about 8,000 square miles. Most of the statistical data for this report is based on the seven core counties of the area which include Blanco, Burnet, Gillespie, Llano, McCulloch, Mason, and San Saba counties.

Climate and Geographic Setting

The climate of the area is subtropical to temperate, subhumid to semiarid, with average annual rainfall ranging from under 26 to over 32 inches, decreasing generally from southeast to northwest. Much of the rainfall occurs in May and September. Figure 2 shows the distribution of annual rainfall, as well as the average monthly precipitation 2 miles north of Brady and at Burnet and Fredericksburg (based on the 31 year period from 1962 to 1992). The average annual gross lake-surface

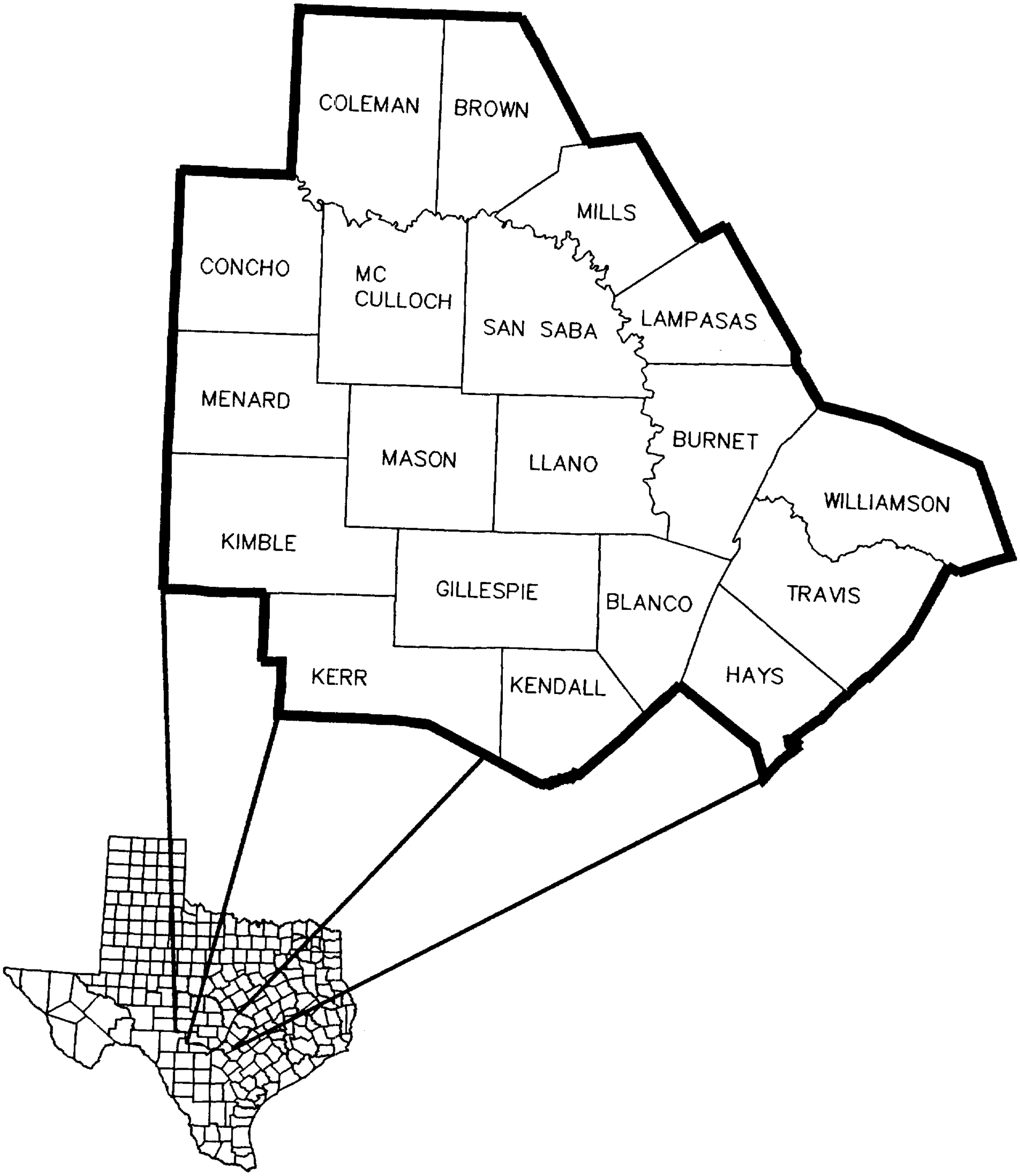


Figure 1. – Location of study area

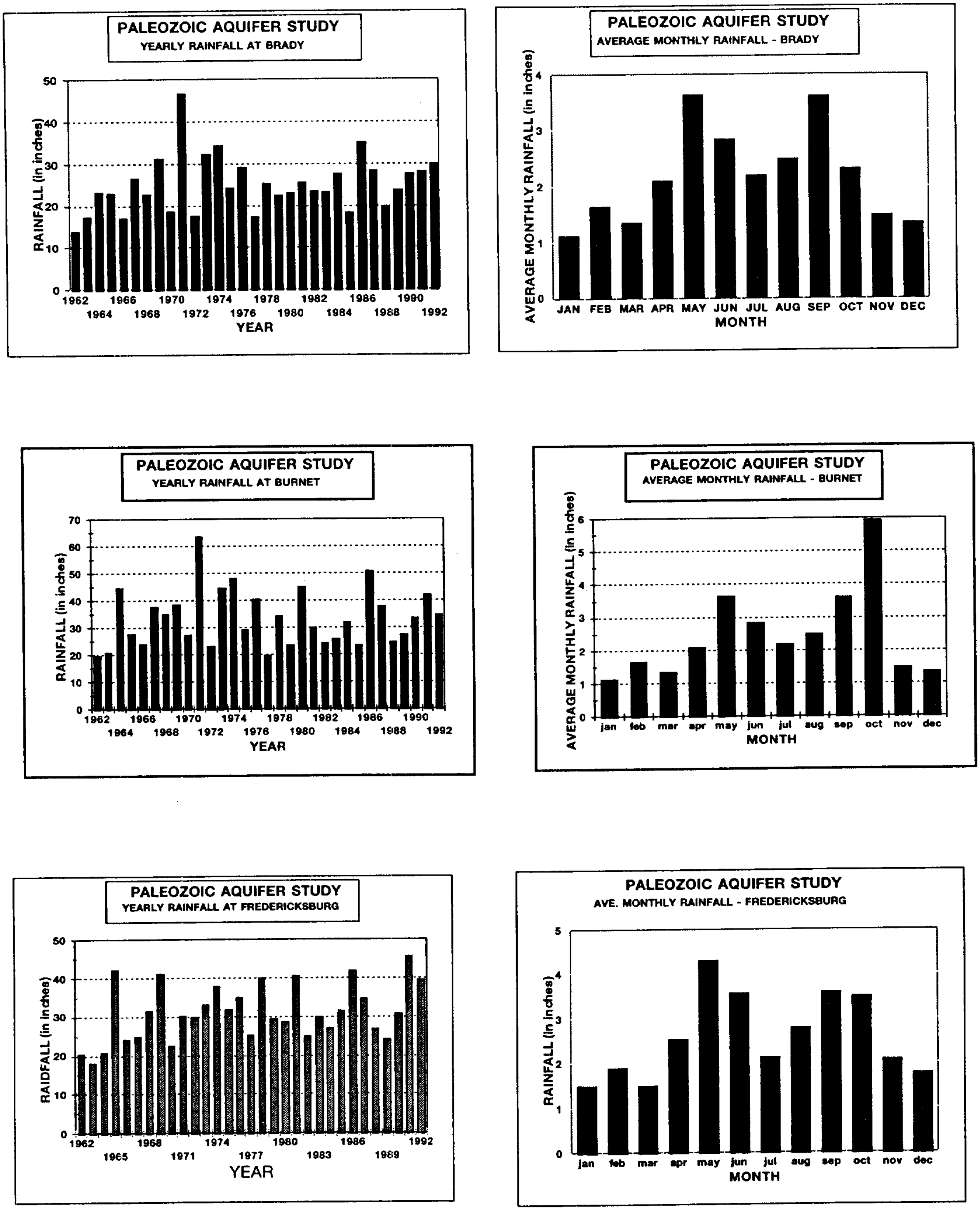


Figure 2. Yearly and Average Annual Rainfall at Selected Sites in the Study Area

evaporation is more than twice the average annual rainfall, ranging from over 70 inches in the northwest part of the area to less than 63 inches in the east. The annual mean temperature ranges from 64° F in the north and west part of the area to 67 in the southeast. The average January low temperature for the same period is 31° in the west and north part of the area and 34° in the south and east. The average July high is 96 or 97° F throughout the area. These figures are based on the 30 year period from 1951 to 1980 (Larkin and Bomar, 1983).

The study area is located mostly within a topographic basin which occupies an eroded domal structure known as the Llano uplift. This general area is also referred to as the Llano Dome, the Llano Basin, and the Central Texas Mineral Region. The area is bounded on the south and west by the Edwards Plateau and on the east by the central Texas hill country, with hills capped by Cretaceous limestones underlain by sands and shales also of Cretaceous age. Portions of both the Edwards Plateau and the central Texas hill country are included in the study area. To the north are flat to rolling plains developed on Pennsylvanian and Permian shales, siltstones, sandstones, and limestones. The area is drained by the Colorado River and its tributaries, including the Pedernales, Llano, and San Saba Rivers, and numerous creeks such as Brady, Baron, Cypress, Cherokee, Sandy, and Threadgill. The topography can be relatively rugged, especially along and near the major streams. The relatively flat inner portion of the basin is characterized by several granite domes, some of which rise several hundred feet above the surrounding surface. These include Enchanted Rock, Smoothingiron Mountain, and Granite Mountain (site of the Texas Pink Granite quarry near Marble Falls).

Economy

The local economy is largely dependent on ranching, farming, and hunting, including both native and exotic game. Irrigation is very important in parts of the area; for peanuts on the outcrop of the Hickory Sand and for peaches in parts of Blanco and Gillespie counties. Tourism also provides a significant contribution to the economy, especially in Fredericksburg and Gillespie County. There is some oil and gas production in outlying areas to the north and west. In addition, there is some production of building stone and aggregate (granite and marble quarries, etc.), as well as frac sand, gypsum, sand, gravel, and minor amounts of other minerals. Manufacturing is important, especially in Brady and Fredericksburg and small business and retailing also contribute significantly.

Previous Investigations

As in most studies, especially regional studies, the work on this project benefitted from earlier investigations. Previous pertinent geologic investigations include Paige (1912), Cloud and Barnes (1948), Stricklin, et al (1971), Rose (1972), Barnes and Bell (1977), and Kupecz (1989). Geologic maps by Barnes (1976) (1981) are important contributions. Ewing (1990) discusses regional tectonics. Reddell (1973) and Reddell et al (1989) discuss caves in the study area. There are also numerous student mapping studies covering USGS 7 1/2 minute topographic maps.

Previous hydrogeologic investigations include Mason (1961), Mount (1967), Bluntzer and Derton (1988), and Bluntzer (1992). Recent theses concerning portions of the study area include Black (1988), Delaney (1990), Pettigrew (1991), and Randoph (1991). These and many additional reference sources are listed in the Selected References Section of this report.

Acknowledgments

The appreciation of the authors and the Board is expressed to our cooperators; the staff of the Lower Colorado River Authority, and the Hickory and Hill Country Underground Water Conservation Districts , as well as to the many city, county, and state officials who aided in many ways. Thanks is also offered to the many private citizens of the region who helped, especially to the many landowners who allowed access to their land and provided additional information on their wells.

Study Personnel

Most of the field work for this study was conducted by Robert L. Bluntzer, Dianne J. Pavlicek, and John Derton. Some additional field work, including measurement of surface-water flows and 1994 water-level measurements was conducted by the above, assisted by Richard D. Preston, Douglas B. Coker, Glynda Mercier, Alfredo Rodriguez, Stephen W. Moore, and Frank Bilberry. Steve Gifford and Mark Hayes completed the illustrations for the report. The report was written by Dianne J. Pavlicek and Richard D. Preston. This study and report was completed under the supervision of Steve Densmore, Water Supplies Section Chief; Tony Bagwell, Water Resources Planning Division Director; and Dr. Tommy Knowles, Deputy Executive Administrator and Director of Planning. Henry J. Alvarez was Section Chief during much of the planning and early field work for this study.

GEOHYDROLOGY

Structure

The major structural feature of the area is the Llano Uplift, a large domal structure, which is now eroded into a topographic basin. Dip in the rocks overlying the basal PreCambrian granites and metamorphics (meta-sedimentary and meta-igneous rocks) of the central dome is in all directions away from the dome (See Figures 3, 4, 5, 6, 7 and 8). Dip varies greatly. Cretaceous rocks dip at a few feet to about 100 feet per mile. Dips in Paleozoic rocks vary greatly from a few tens of feet per mile in much of the area to several hundred feet per mile near buried PreCambrian highs. Other major structural features which may effect ground water include the San Marcos Arch, the Concho Arch, and the Balcones Fault Zone. A major system of faults associated with the Paleozoic rocks occurs in and around the uplift (see Figure 8). The faulting appears to have occurred in Pennsylvanian time. The faults trend northeast - southwest and have throws ranging from a few feet to over 500 feet.

The San Marcos Arch, a subsurface extension of the Llano Uplift, is a broad anticlinal feature which plunges to the southeast from central Blanco County across Comal and Hays counties. This feature is recognized mostly in the Paleozoic rocks but causes some thinning in the overlying Cretaceous. The Fredericksburg high which extends south-southwest from north central Gillespie County through Kendall and Kerr counties to Bandera County is probably associated with the San Marcos Arch. It represents a high ridge in the Paleozoic and PreCambrian rocks, but may be a long fault block or a connected series of fault blocks.

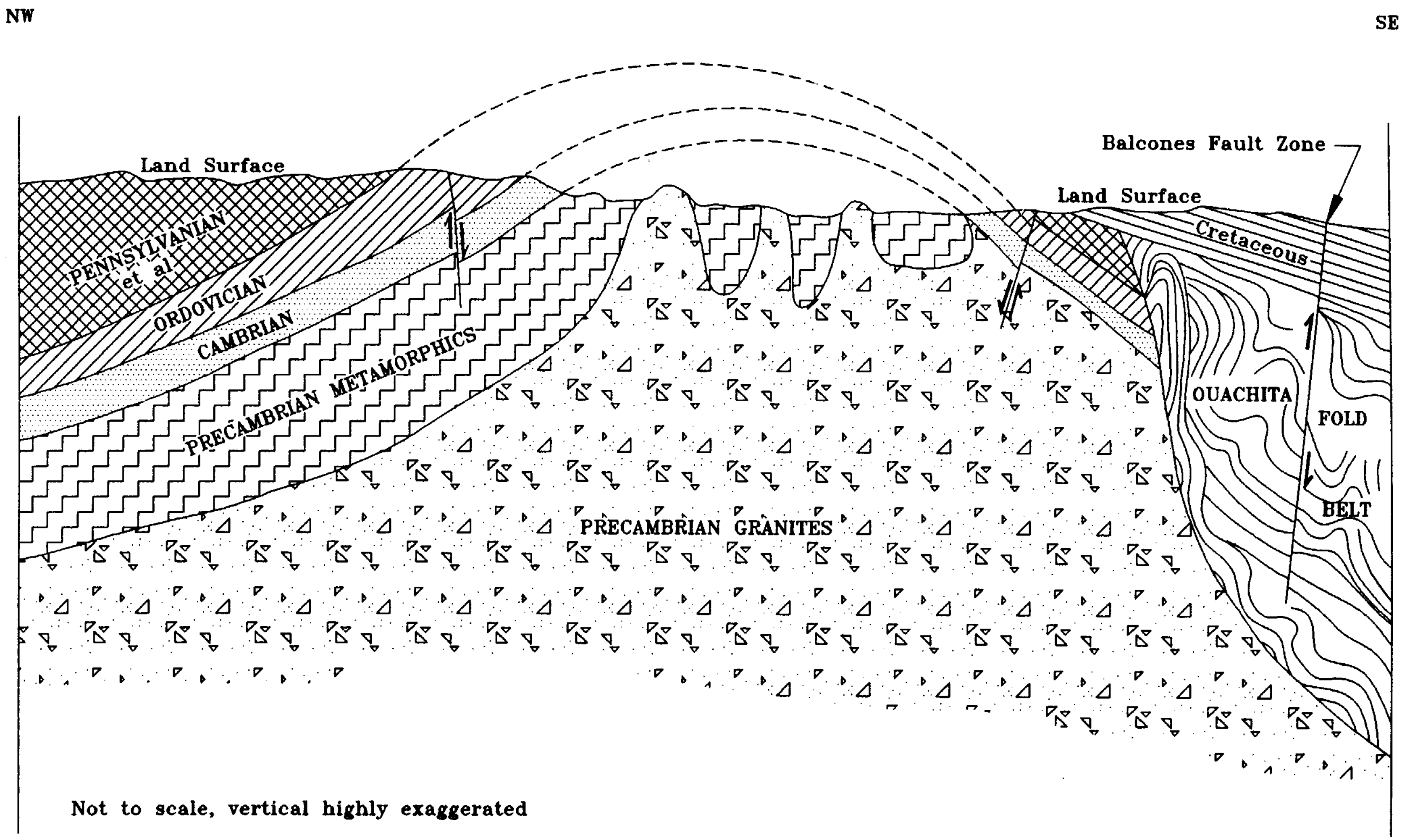
The Balcones Fault Zone is an elongate system of normal faults which stretches around the study area on the south and east. It is associated with the buried Ouachita Fold Belt, which is the remnant of an ancient, highly-eroded mountain range. The fault zone represents a line of flexure between the more stable central Texas area and the sinking coastal plain.

The Concho Arch, an elongated domal structure, was uplifted during early Pennsylvanian time. The Arch extends northwestward through Concho County.

Stratigraphy

PreCambrian

PreCambrian formations consist of a complex system of meta-sedimentary and meta-igneous rocks cut and/or pierced by igneous rocks. Major meta-sedimentary rock units are the Packsaddle Schist and the Valley Spring Gneiss; meta-igneous rocks are the Coal Creek Serpentine, Big Spring Gneiss, and Red Mountain Gneiss. The Lost Creek Gneiss is either meta-igneous or meta-sedimentary. Igneous rocks of the area include the Llanite Quartz Porphyry, the Sixmile Granite, the Oatman Creek Granite, and the Town Mountain Granite. These rocks cropout in the center of the Llano Uplift and underlie younger sediments around the uplift. The stratigraphy of these sediments is very complicated and, since they do not effect the aquifers, they will not be discussed further. Locally, where fractured and highly weathered, these rocks provide minor amounts of water to very shallow wells. Several reports listed in the Selected References Section discuss these rocks in detail. Table 1 and Figures 3, 4, 5, 6, 7, and 9 graphically illustrate the stratigraphy of the region.



Not to scale, vertical highly exaggerated

Figure 3. – Idealized geologic cross-section, Llano Uplift

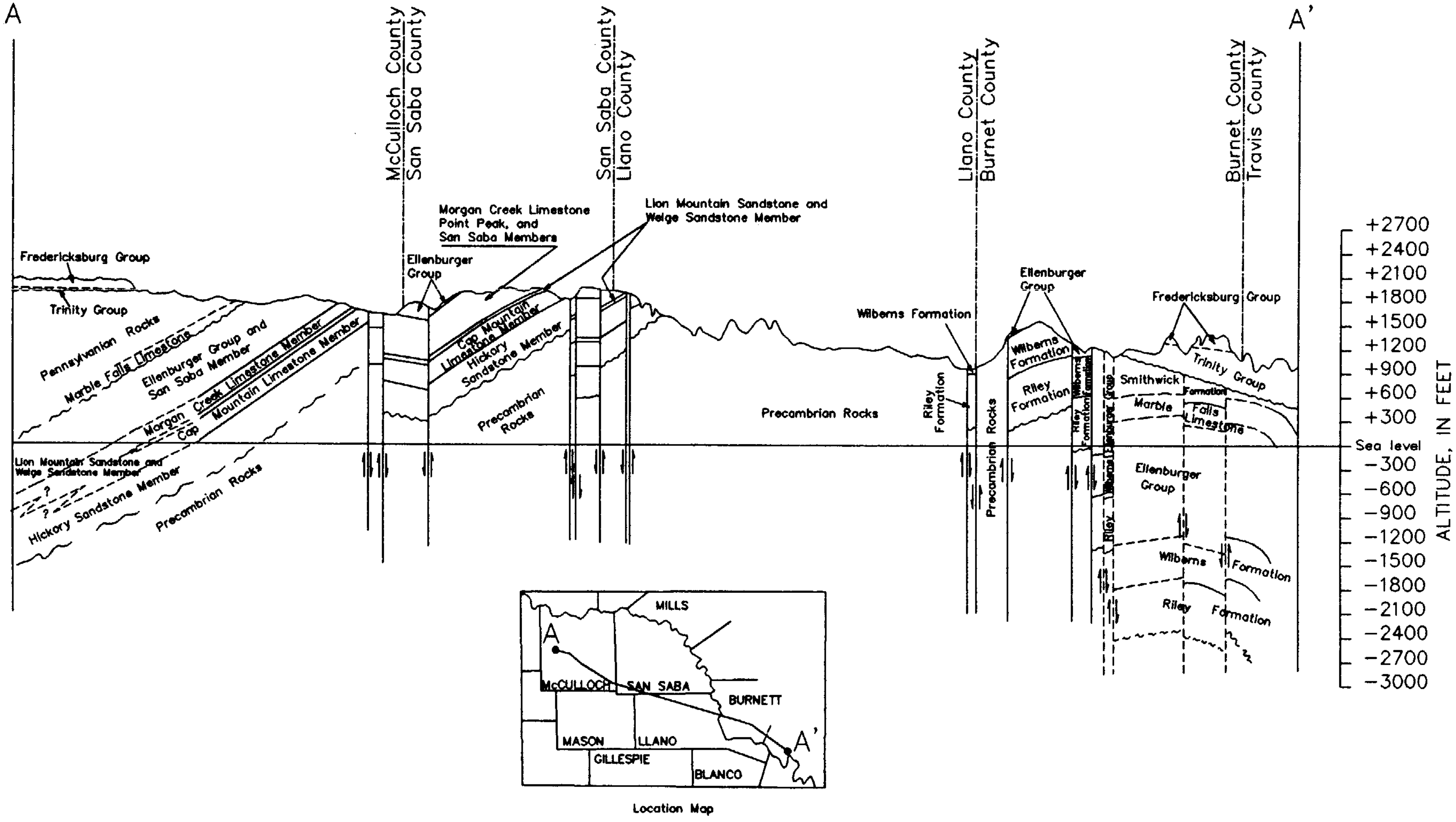


Figure 4. – Generalized geologic cross-section A–A' across the Llano uplift (adapted from Mount and others, 1967)

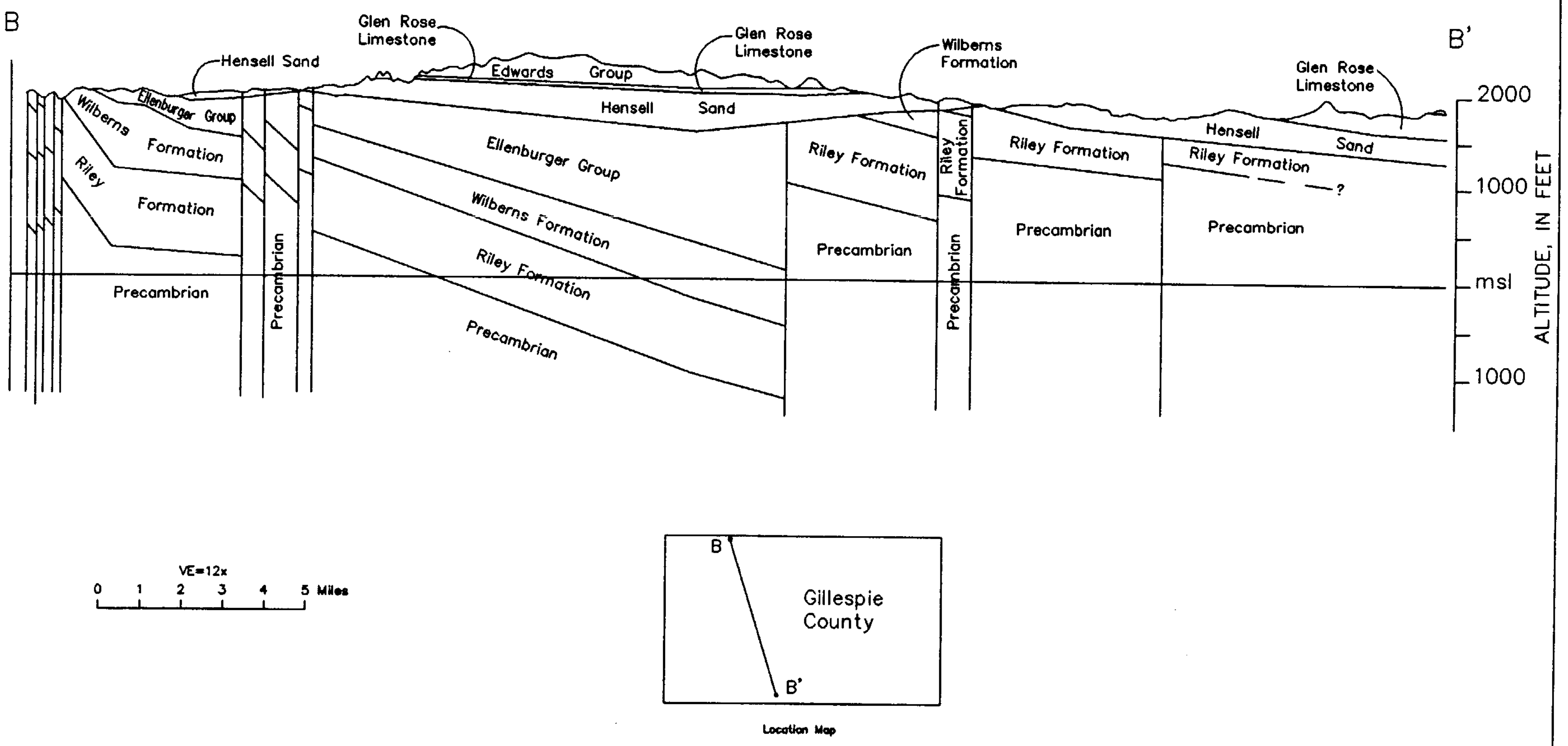


Figure 5. – Cross-section B–B' adapted from Jackson and Tyber (1993).

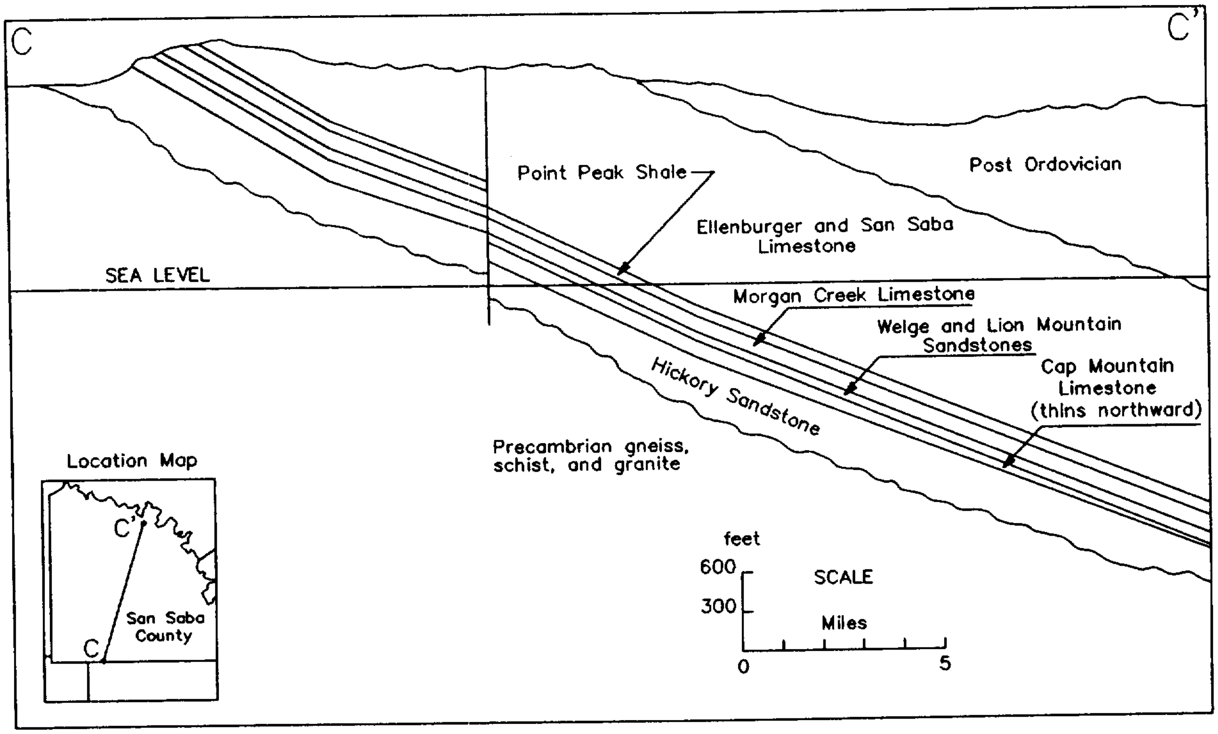


Figure 6. – Cross section C–C' (adapted from Pettigrew, 1991)

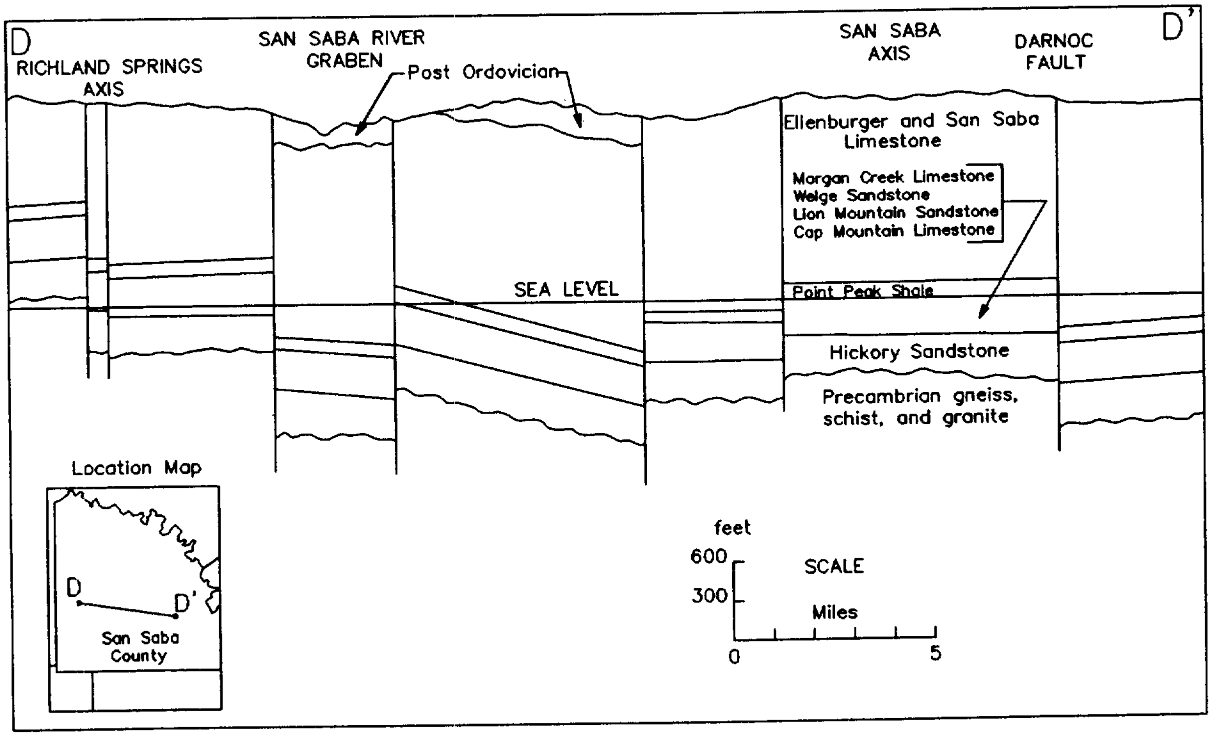


Figure 7. – Cross-section D–D' (adapted from Pettigrew, 1991)

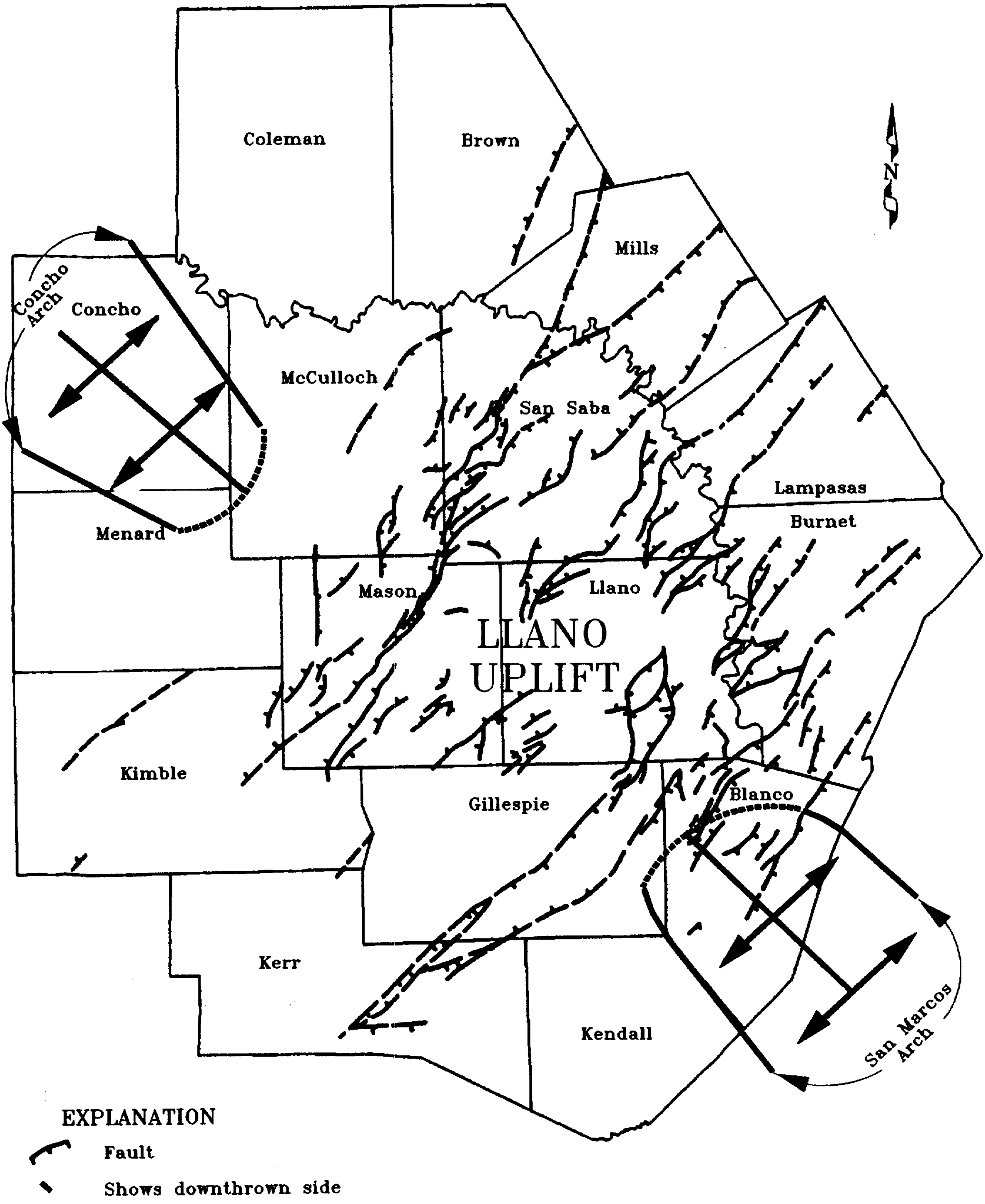


Figure 8. – Generalized tectonic map of the study area

Table 1. Geologic and hydrogeologic units in the study area.

Geologic Units						Hydrogeologic Units	
Era	System	Group		Formation	Member or Unit		
Cenozoic	Quaternary	Pleistocene to Recent floodplain (alluvium and fluviatile terrace deposits)				localized alluvial aquifers	
Mesozoic	Cretaceous	Edwards Group		Segovia Formation		Edwards Plateau Aquifer	Edwards Trinity aquifer
				Fort Terrett Formation	Kirchburg evaporite Mbr.		
					Dolomite Mbr.		
					Burrowed Mbr.		
					Basal nodular bed Mbr.	confining bed	
		Trinity Group		Glen Rose Limestone	Upper member	Upper and Middle Trinity aquifer	
			Travis Peak equivalent	Hensell Sand Bexar	Lower member		
				Cow Creek Limesone			
				Hammett Shale		confining bed	
				Sligo Sycamore Sand Hosston		Lower Trinity aquifer	
Paleozoic	Pennsylvanian	Canyon Group		undivided		confing beds	
		Strawn Group		undivided			
		Bend Group		Smithwick	undivided		
				Marble Falls Limestone		Marble Falls aquifer	
	Mississippian and Devonian	Consists from youngest to oldest of Barnett Formation (Mississippian), Chappel Limestone (Mississippian), Houy Formation (Denovian), and Stribling Formation (Devonian).				Usually confing beds where present	
	Ordovician	Ellenburger Group		Honeycut Formation	undivided	Ellenburger-San Saba aquifer	
				Gorman Formation	undivided		
				Tanyard Formation	Staendebach Member		
					Threadgill Member		
	Cambrian	Moore Hollow Group		Wilberns Formation	San Saba Member		
					Point Peak Member	confining beds	
					Morgan Creek Limestone Member		
					Welge Sandstone Member	Mid-Cambrian aquifer	
				Riley Formation	Lion Mountain Sandstone Member		
					Cap Mountain Limestone Member	confining beds	
					Hickory Sandstone Member	Hickory aquifer	
Precambrian		Llanite Oatman Creek Granite Six Mile Granite Pegmatite and quartz veins Town Mountain Granite Melaryolite dikes Red Mountain Gneiss Coal Creek Serpertine Mafic igneous rocks Packsaddle Schist Lost Creek Gneiss Valley Springs Gneiss				Usually confining beds	

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The Hickory Sandstone Member of the Riley Formation of the Moore Hollow Group was deposited on an irregular erosional surface probably quite similar to the surface of the PreCambrian rocks exposed in the center of this region today. There was a maximum local relief of about 800 feet, mostly where granite domes stand above the surrounding low relief surface developed on gneisses, schists, and softer granites. In places, these PreCambrian hills extend up into the overlying Cap Mountain Limestone or higher, and the Hickory may be entirely absent. Thickness of the Hickory ranges up to nearly 500 feet (Barnes and Bell, 1977)and generally thins southward, however. As an aquifer, the Hickory provides moderate to large amounts of good-quality water to wells down to depths in excess of 3,000 feet.

The contact of the Hickory with the overlying Cap Mountain is gradational and is arbitrarily mapped as the first bed where there is more lime than sand. Therefore, there are usually some limy sands mapped in the Hickory and some sandy limes mapped in the Cap Mountain. The Hickory is almost entirely made up of crossbedded quartz sandstone. It is generally thin-bedded in the upper third, with medium to thick beds in the middle, and very massive beds in the basal part. At a few locations, parts of the very lowest beds may be conglomeratic. Rarely there are some pebbles of feldspar in the basal beds, but this is usually near a buried granite hill. Some isolated quartz pebbles in the basal part of the Hickory exhibit wind faceting, but bedding characteristics, sorting, and the occasional presence of trilobite trails indicate deposition in shallow seas. Commonly, the uppermost beds of the Hickory contain large amounts of iron (hematite), and in fact commercial mining operations have been considered in a few locations. The color of the Hickory varies from white to yellow to brown, with the iron-rich beds a red-brown to almost black.

The Cap Mountain consists of thin beds of limestone with considerable sand in the lowermost beds and grades upward to thicker beds of siltstone, silty limestone, and limestone. The limestones are glauconitic, with some oolites, and are generally some shade of gray or brown. Formation thickness ranges from about 500 to 650 feet and generally thins northwestward. The contact of the Cap Mountain with the overlying Lion Mountain Sandstone seems to be unconformable.

The Lion Mountain Sandstone, uppermost Member of the Riley Formation, consists of relatively thin beds of glauconitic quartz sandstone, quartzose greensand, impure fossiliferous limestone, crossbeds of trilobite coquinite, and a few thin beds of shale and siltstone. Thickness varies from 25 to 85 feet and generally thins to the southeast. The Lion Mountain, together with the overlying Welge Sandstone, forms a water-bearing zone, referred to here as the Mid-Cambrian aquifer, providing small to moderate amounts of water to a few wells on or near the outcrop.

The contact with the overlying Welge Member of the Wilberns Formation appears to be unconformable, but is hard to recognize in the subsurface, unless drill cuttings are available, because there is much less glauconite in the Welge. The Welge Sandstone is the lowermost member of the Wilberns Formation of the Moore Hollow Group. It consists of thick-bedded brown to yellow sandstone with only minor amounts of glauconite. The quartz sand is usually medium grained and varies from brown to yellow in color. The thickness varies from 5 to over 30 feet and thins to the southeast.

Lying unconformably above the Welge Member is the Morgan Creek Member of the Wilberns. It consists of thick to thin bedded limestone. The beds are mostly fossiliferous and are often granular and glauconitic. The beds vary from pink to reddish-brown to gray to greenish and brownish gray in color. Thickness of the Morgan Creek Member ranges from 90 to 190 feet, generally thinning to the southeast.

Above the Morgan Creek in the Wilberns is the Point Peak Member, often called the Point Peak Shale, which consists predominantly of laminated siltstone, with some thin beds of limestone and shale. In the subsurface of western McCulloch and eastern Concho counties, this interval contains some sand, and in at least one well in the vicinity of the community of Melvin water is reported to be produced from Point Peak sands. The color of these rocks is generally gray. The thickness ranges from 0 to 220 feet and pinches out to the southeast. Together, the Morgan Creek and Point Peak form a confining layer between the Mid-Cambrian aquifer and the overlying Ellenburger-San Saba aquifer.

The uppermost member of the Wilberns Formation is the San Saba Limestone, which consists of limestone and dolomite. It is thickly- to thinly-bedded and colored yellow to brown to medium gray. The dolomite is fine- to very fine-grained and contains some chert. The Member varies in thickness from 250 to 850 feet and thins to the north. The very upper part of the formation is now considered to be Ordovician in age by most geologists. Therefore the Cambrian - Ordovician contact is now considered to be in the upper part of the San Saba Limestone Member of the Wilberns Formation. The contact of the Moore Hollow Group and the overlying Ellenburger Group is thought to be conformable at least over most of its extent. Together with the overlying Ellenburger formations, the San Saba forms an aquifer, providing moderate to large amounts of usable-quality water down to depths of over 2,000 feet.

The Ellenburger Group consists of three formations named, in ascending order, the Tanyard, Gorman, and Honeycut. The thickness of the Tanyard Formation varies from 475 to 730 feet and thins to the west. The Tanyard Formation is locally divided into two members, the basal Threadgill Member and the overlying Staendebach Member. The Threadgill is predominantly made up of light gray dolomite, both thick- and thin-bedded. The dolomite is medium- to coarse-grained and laterally grades into massive light gray limestone in some locations. Though most now agree that the Cambrian - Ordovician contact lies within the upper San Saba, a few still feel that the basal part of the Threadgill Member may be Cambrian in age.

The Staendebach Member consists of thin- to thick-bedded limestone and dolomite. The limestone is very fine-grained, light gray in color, and is usually cherty. The dolomite is gray to brownish gray in color and is fine- to medium-grained. The dolomite also contains chert nodules. Most of the chert throughout the member is fossiliferous.

Devonian and Mississippian age formations in the study area consist of thin, scattered-discontinuous remnants of dark shales, petroliferous limestones, crinoidal limestone, chert breccias, fractured cherts, and microgranular limestones with bedded chert. Thickness ranges from 0 to 50 feet. Formations which may be present are, from oldest to youngest, the Stribling Formation (Devonian), Houy Formation (Devonian), Chappel Limestone (Mississippian), and Barnett Formation (Mississippian) (Bluntzer, 1992). These formations are generally non-water bearing.

Pennsylvanian formations rest unconformably on either the rocks of the Ellenburger Group or the Devonian-Mississippian formations. The Lowermost are the Marble Falls and Smithwick formations of the Bend Group. The Marble Falls Limestone locally consists of a lower and upper unit. The thickness of the formation ranges from 385 to 460 feet. The lower unit is mostly massive limestone reef deposits. The limestone is very high calcium and generally very fine grained. It is gray in color with some thin shale stringers in the lowermost few feet. The upper unit is mostly thin to thick bedded limestone. The limestone is very fine grained and contains chert nodules and beds. It is fossiliferous and brownish to olive in color. The overlying

Smithwick Formation consists of 300 to 500 feet of interbedded claystone, siltstone, and sandstone. The Marble Falls is an aquifer and provides small to moderate amounts of usable-quality water to wells at or near the outcrop.

Above the Bend Group and onlapping from the west and northwest are rocks of the Strawn and Canyon Groups also of Pennsylvanian age. They range from 0 to 1,500 feet in thickness and generally consist of interbedded limestone, shale, and fine grained sandstone.

Cretaceous

A considerable amount of time is represented by the major unconformity between the older rocks discussed so far and the younger Cretaceous rocks. On this unconformable surface Cretaceous seas, which advanced from the southeast, deposited the formations of the Trinity and Fredericksburg groups. Cretaceous formations at one time covered the entire region, but have been removed by erosion except for the outer edges of the study area. The Trinity Group is represented by the Travis Peak Formation and the overlying Glen Rose Limestone. The Travis Peak has been divided into, from oldest to youngest, the Hosston , Sligo, Hammett, Cow Creek, Bexar, and Hensell Members. The Sligo is at least partially equivalent to the upper part of the Hosston and the Bexar Member is a downdip facies of the Hensell.

The Hosston consists of interbedded sandstone, siltstone, claystone, shale, dolomite, and limestone, and a basal conglomerate. The Hosston varies in thickness from 0 to 350 feet and pinches out to the north and northwest. The Sligo consists of 0 to 120 feet of sandy dolomitic limestone, limestone, dolomite, and shale. It also pinches out to the north and northwest. Updip in some parts of the outcrop the equivalent rocks of the Hosston and Sligo are called the Sycamore Sand. Together, the Hosston and Sligo (or Sycamore) form the Lower Trinity aquifer.

The Hammett consists of shale interbedded with thin beds of limestone and sand. The shale is calcareous, fossiliferous, and dolomitic. It is dark blue and gray to greenish gray in color, 0 to 60 feet thick and also pinches out to the north and northwest. The Hammett forms a confining bed above the Lower Trinity aquifer.

The Cow Creek Limestone Member consists of massive, locally crossbedded, highly fossiliferous limestone, which may be sandy, argillaceous, and dolomitic. In color it varies from white to gray, and locally is interbedded with thin sands, shales, lignites, gypsum, and anhydrite. The thickness ranges from 0-100 feet and pinches out to the north and northwest.

The Hensell Sand Member consists of interbedded red to gray clay, silt, sand, sandstone, conglomerate, and thin limestone. The quartz sands are generally fine to medium grained, but may be silty and very fine grained in some areas, especially to the north. The thickest sands and sandstones are immediately adjacent to the south and east parts of the Llano Uplift. On the south side of the study area, the Hensell grades downdip into the Bexar Shale Member, which consists of a relatively thin sequence of silty dolomite, marl, calcareous shale, and shaley limestone. The Hensell/Bexar Member ranges from 10 to about 300 feet in thickness, thinning to the east and south. The Glen Rose Limestone is divided into Lower and Upper Members based on a persistent fossiliferous bed containing large amounts of the small round shell named Corbula. The basal part of the Lower Member consists of massive fossiliferous limestones and limestone reefs which grade upward into thinner beds of limestone, dolomite, marl, and shale. The massive beds and reefs often are cavernous. The color is white to gray, and the unit ranges from 0 to 400 feet in thickness. The lower unit pinches out toward the Llano Uplift, and thins toward the northwest. The Corbula bed is considered the top of the lower unit. The upper unit consists of interbedded fossiliferous limestone, porous dolomite, and nodular marl. Most of the beds alternate between resistant (hard) and recessive (soft) in weathering characteristics which give the outcrop slopes of this unit a distinctive stairstep or terraced look. In general the upper unit is less fossiliferous, more dolomitic, and thinner bedded than the lower unit. There are two distinct evaporite zones within the upper unit containing both gypsum and anhydrite. These are responsible for the gyppy water often associated with the Upper Member. The thickness of this unit varies from 0 to 515 feet and it also pinches out toward the Llano Uplift and thins to the northwest. In the southeast, east, and northeast parts of the study area the Glen Rose, Hensell, and Cow Creek form an aquifer which provides small to moderate amounts of usable-quality water to wells down to depths of about 1,000 feet.

In the study area, the overlying Fredericksburg Group of the Cretaceous occurs in the southwest and west parts, with only the lowermost formation of the group, the Edwards Limestone, represented. In this area, the formation is divided into two members, The Fort Terrett and the Segovia. Barnes (1981) and Bluntzer (1992) describes these two members as follows:

Fort Terrett Member, "Lower Part (Quarter) - Nodular limestone and yellow fossiliferous clay at base which is equivalent to 'Walnut Formation'. Middle Part - Gray, cherty, fossiliferous limestone and brownish-gray dolomite. Upper Part (Quarter) - Porcelaneous aphanitic limestone with collapse breccia, chert, and recrystallized limestone."

Segovia Member, "Lower Part - Yellowish-gray, fossiliferous limestone and marl and marly limestone. Middle Part - Brownish-gray, porous, cherty, massive to thin-bedded dolomite with collapse breccia. Upper Part - Cherty, light-gray, fossiliferous limestone."

The Fort Terrett Member ranges from 150 to 300 feet in thickness and thickens southward; the Segovia from 170 to 380 feet and also thickens to the south. In the west and southwest parts of the study area the Edwards and the underlying Trinity Group rocks form an aquifer, the Edwards-Trinity (Plateau) aquifer, which provides moderate amounts of good-quality water to wells.

Pleistocene-Recent

Locally and erratically overlying any or all of the older rocks are Pleistocene to Recent floodplain, terrace, and other alluvial deposits mostly still associated with existing waterways. They consist of interbedded deposits of clay, silt, sand, gravel, and caliche and vary in thickness up to about 50 feet. Locally these sediments provide small to moderate amounts of usable-quality water to wells.

Delineation and Relationship of Aquifers

Several aquifers provide water within the study area. These include, the Hickory, Mid-Cambrian, Ellenburger-San Saba, and Marble Falls (See Figure 10). The Trinity Group aquifer, the Edwards-Trinity Plateau aquifer, and various recent alluvial aquifers are also important in parts of the area.

In general, the Paleozoic formations, Cambrian Riley Formation (Hickory aquifer and lower part of the Mid-Cambrian aquifer), Cambrian Wilberns Formation (upper part of the Mid-Cambrian aquifer and lower part of the San Saba-Ellenburger aquifer), Ordovician Ellenburger Group (upper part of the Ellenburger-San Saba aquifer), Pennsylvanian Marble Falls Limestone (Marble Falls aquifer) cropout in more-or-less concentric rings around the center of the basin. These outcrop patterns are further complicated and broken by the complex faulting associated with the uplift. Cretaceous Trinity and Fredericksburg Groups (Trinity and Plateau aquifers) also surround the uplift and lap up on the underlying formations, forming a broken ring of hills around the basin. Very minor but locally important aquifers are developed in weathered zones on outcrops of PreCambrian granites, gneisses, and schists and in alluvial deposits along rivers and creeks. As shown on the Generalized Aquifer Map and the Geologic Cross Sections (Figures 4, 5, 6, and 7), the Hickory overlies the PreCambrian rocks and dips away from the center of the uplift, passing under the outcrop of younger and then younger rocks. The Mid-Cambrian crops out and then dips under the San Saba. The Ellenburger dips under the Marble Falls, and then the Marble Falls under younger Pennsylvanian rocks. All of these aquifers contain usable quality water for at least a short distance downdip of their outcrop, with the Hickory and Ellenburger containing good water down to quite some depth and distance from the outcrop as shown on the aquifer map (Figure 10).

Recharge, Movement, and Discharge of Ground Water

Rainfall and stream runoff are the major sources of recharge, which is the process or processes by which water is added to an underground water-bearing formation (aquifer). The major controlling factors are the frequency and intensity of this precipitation and the areal extent of the outcrop of the formation. Other significant factors controlling recharge include topography, amount and kind of vegetative cover, soil conditions and characteristics, and the hydraulic conductivity of the rocks that make up the aquifer. Most recharge to the Hickory and Mid-Cambrian aquifers is from rainfall on the sandy outcrop, but a significant amount occurs where rivers and tributaries cross the outcrops of the aquifers. Most recharge to the limestone and dolomite aquifers (Ellenburger-San Saba and Marble Falls) occurs through faults, especially at stream crossings. There is also a considerable amount of rejected recharge in the form of springs and seeps, which are likewise often associated with faulting.

Numerous sinkholes, caves, and other karstic features exist on the outcrop of the Ellenburger and San Saba limestones and dolomites. There are also some buried erosional surfaces within the Ellenburger Group rocks with additional ancient karst features which add to the porosity and permeability of this aquifer. Most of these karstic features, as well as the seeps and springs, are associated with faulting. These features not only add considerably to the ease of recharge to the aquifer, but constitute pathways to the surface for a significant amount of rejected recharge.

Ground-water movement is controlled by gravity and hydrologic pressure, and is generally from areas of recharge to areas of discharge. Its direction and rate is influenced by a variety of factors which include the physical nature of the rocks which make up the aquifer—their composition and configuration; the external pressures applied to the formation; and the fundamental physical laws of gravity and momentum. Also included in these factors are surface tension, friction, atmospheric pressure where the formation encounters the earth's surface, paths of differential permeability, effects of heavy local withdrawal or injection of water, and climatic changes affecting rates of recharge. In most cases, the rate of movement is relatively slow, from a few inches to a few hundred feet per year. Movement in sand aquifers is generally on the slow end of the spectrum. The higher rates are most often found in highly fractured and solutioned limestone and dolomite aquifers. Locally, pumping of wells and well fields can alter both the velocity and direction of ground-water movement, almost always increasing the speed of movement toward the center of pumpage.

Discharge is the sum of those processes which remove water from an aquifer, and may be from both natural and artificial means. The natural discharge of ground water within the study area is through the numerous springs and seeps. Some of the largest springs in Texas are located here, including those at the community of San Saba and several along the Colorado River in eastern San Saba County. There is also some interformational movement in the downdip area, mostly upward, probably discharging through springs and seeps to the major streams. Artificial discharge is pumpage from wells. Much of the initial flow in the Pedernales, San Saba, and Llano rivers comes from springs and seeps derived from the dissected Edwards-Trinity (Plateau) aquifer.

Stream Gain - Loss

A gaining stream is one receiving additional flow through a reach, usually from ground-water discharge. A losing stream is one recharging a ground-water system (Todd 1980). The Board conducted a low-flow study to determine and evaluate gain-loss conditions within the study area. Stream gain-loss measurement sites were selected primarily within the Colorado, San Saba, Pedernales and Llano river drainage. Many of the measurement sites were located to determine gain or loss of flow across the major faults or fault zones displacing Paleozoic rocks in the region. Flow data was collected during February and March 1994, during a time period of low evapotranspiration and no irrigation. Return flows were minimal at this time. Flow velocity was measured using a flowmeter with an electromagnetic sensor. Data from the San Saba and Pedernales rivers are discussed here. A compilation of all data that were collected is summarized in an open-file data report by Pavlicek and Hayes (1994).

The San Saba River profile (Figure 11, Table 2) indicates an assortment of gains and losses. Losses associated with faulting occur between points 1-2, 2-3, 7-8, 9-10, 11-12, and 16-17. Gains associated with faulting occur between points 3-4. Points 10-11 show a gaining reach associated with Hickory aquifer discharge as the river crosses an outcrop of Hickory Sandstone. Gains associated with points 13, 14 and 15 are due to spring discharge from the Gorman Formation.

The Pedernales River profile (Figure 12, Table 3) shows an overall gaining reach with significant discharge from the base of the Edwards Group and the Hensell Sand from points 1-10. Spring discharge from Paleozoic formations begin to contribute to baseflow between points 10-20. Note the dramatic change in specific conductance between points 15-21, probably indicating waters with a shorter residence time within the aquifer.

The following are some additional notes on historic baseflow studies:

Black (1988) found that the San Saba river gains and loses significant quantities of water to/from the ground-water systems.

Holland and Lee (1956) investigated the baseflow of the Pedernales River system along a 70 mile reach from Harper (Gillespie County) to Johnson City (Blanco County) during a drought period in 1955 - 1956. They found that the Pedernales River system's baseflow is derived from: 1) headwater springs issuing from the base of the Edwards near Harper on the main stem and along some tributaries, 2) contributions from extensive areas of Hensell Sand through tributaries and seepage into alluvium, 3) springs and seeps originating in areas of faulting, jointing and dissolution in Cretaceous and Paleozoic carbonate rocks. The Pedernales River generally gained in flow. No areas were found where substantial losses could be attributed to seepage into the ground-water system. Losses were principally due to evaporation, transpiration and to irrigation pumpage. The findings of Holland and Hughes (1964), using data collected in 1962, agree with the investigation made in 1956 by Holland and Lee. They specify that small quantities of water that are lost in areas of faulting, jointing and solution channeling probably do not leave the river valley.

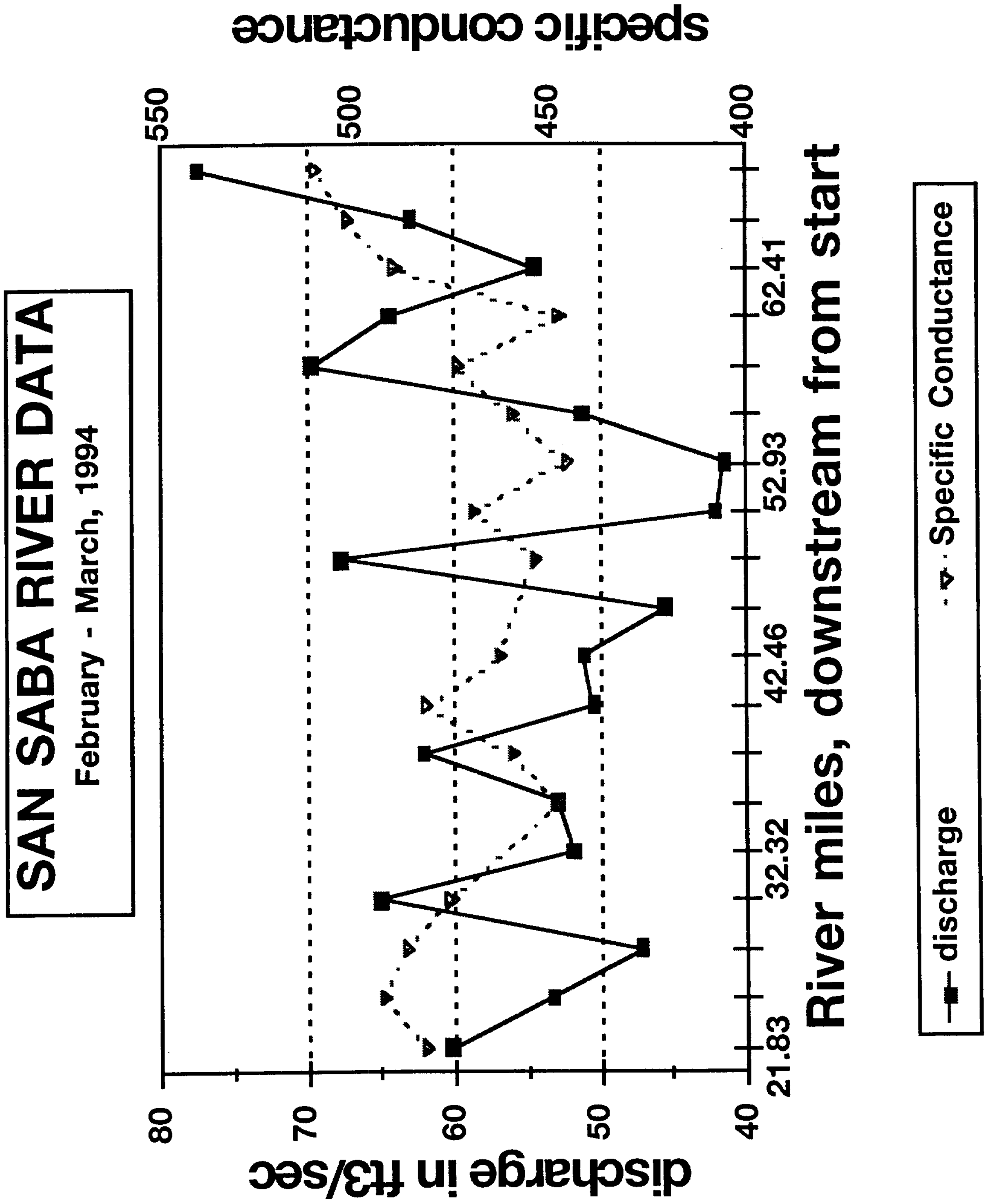


Figure 11. Flow and Specific Conductance Profile of Reach of the San Saba River

Table 2. Flow Data for San Saba River

Measurement Site	Total Flow (cubic feet per second)	Specific Conductance (microsiemens)	Geology at Site
1. San Saba River #1	60.22	482	Canyon Group
2. San Saba River #2	53.33	493	Gorman Formation
3. San Saba River #5	47.13	487	San Saba Limestone
4. San Saba River #6	65.06	476	Gorman Formation
5. San Saba River #7	51.95	-	San Saba Limestone
6. San Saba River #9	53.02	449	San Saba Limestone
7. San Saba River #10	62.08	460	Lion Mountain Sandstone
8. San Saba River #11	50.46	482	Tanyard Formation
9. San Saba River #12	51.14	463	Tanyard Formation
10. San Saba River #13	45.53	-	Hickory Sandstone
11. San Saba River #14	67.69	454	San Saba Limestone
12. San Saba River #15	42.06	470	San Saba Limestone
13. San Saba River #16	41.49	446	Gorman Formation
14. San Saba River #17	51.24	460	Gorman Formation
15. San Saba River #18	69.72	474	Gorman Formation
16. San Saba River #19	64.41	448	Marble Falls Formation
17. San Saba River #20	54.52	490	Marble Falls Formation
18. San Sabe River #21	63.0	502	Marble Falls Limestone
19. San Saba River #22	77.54	510	Smithwick Formation

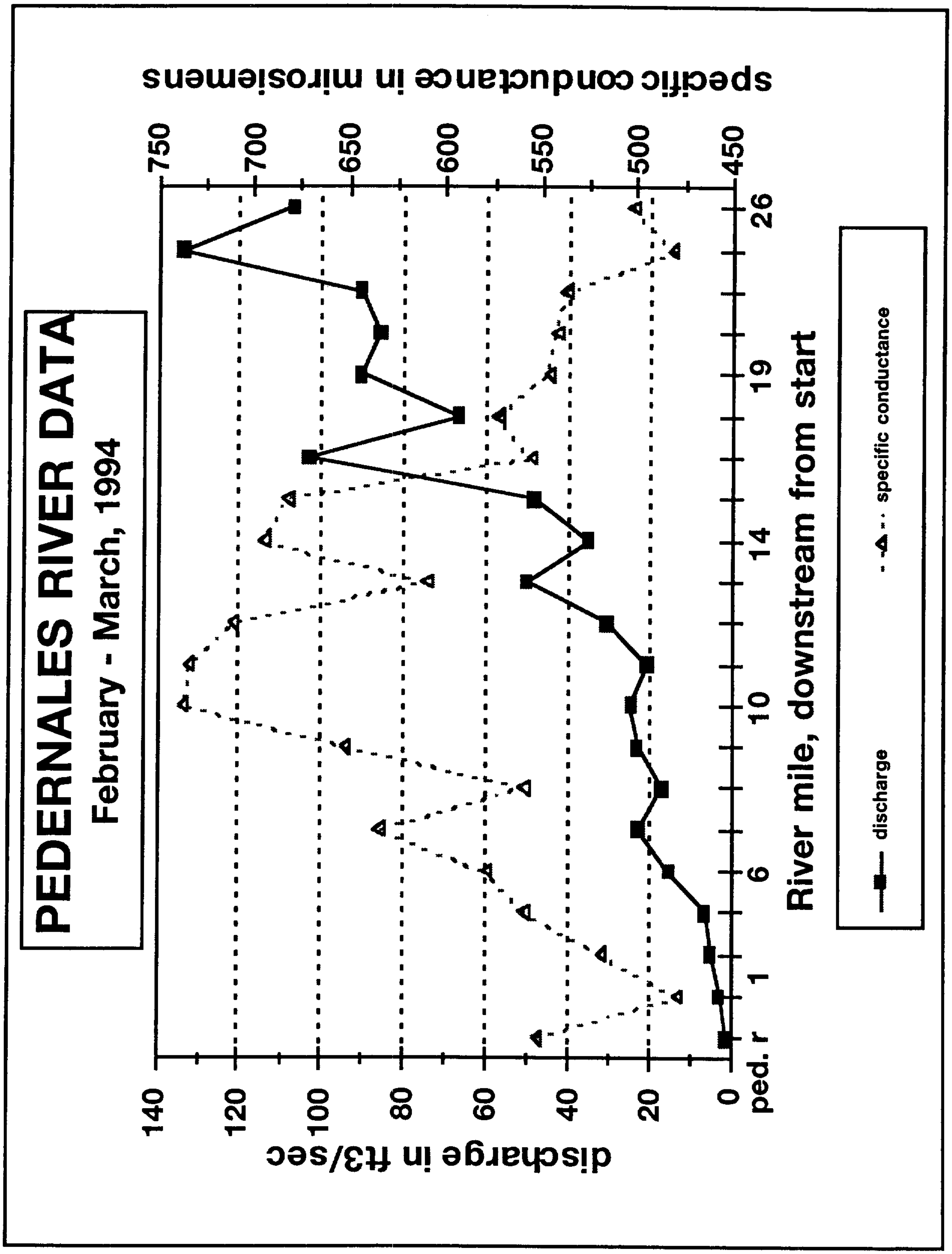


Figure 12. Flow and Specific Conductance Profile of Reach of the Pedernales River

Table 3.- Data for Pedernales River.

Measurement Site	Total Flow (cubic feet per second)	Specific Conductance (microsiemens)	Geology at Site
1 Pedernales River #1	1.41	552	Edwards - Glen Rose
2 Pedernales River #2	2.95	478	Glen Rose Formation
3 Pedernalws River #3	5.15	518	Cap Mountain Limestone
4 Pedernales River #4	6.62	559	Hensell Sand & Alluvium
5 Pedernales River #6	15.29	578	Hensell Sand & Alluvium
6 Pedernales River #7	22.96	634	Hensell Sand & Alluvium
7 Pedernales River #8	16.90	559	Hensell Sand & Alluvium
8 Pedernales River #9	23.07	652	Hensell Sand & Alluvium
9 Pedernales River #10	24.69	736	Hensell Sand & Alluvium
10 Pedernales River #11	20.66	733	Hensell Sand & Alluvium
11 Pedernales River #12	30.59	710	Ellenburger Group
12 Pedernales River #13	50.31	610	Paleozoic carbonates
13 Pedernales River #14	35.24	694	Ellenburger Group
14 Pedernales River #15	48.55	682	San Saba Member
15 Pedernales River #16	103.2	555	Cap Mountain Limestone
16 Pedernales River #17	66.85	573	San Saba Member
17 Pedernales River #19	90.56	546	Cap Mountain LImestone
18 Pedernales River #21	85.92	542	Gorman Formation & Alluvium
19 Pedermales River #23	90.54	537	Honeycut Formation
20 Pedernales River #25	133.87	481	Marble Falls Formation
21 Pedernales River #26	107.17	502	Sycamore Sand

Texas Board of Water Engineers (1960) presents historic data from the San Saba River system, but a discussion is not included. Data from 1918 from near Ft. McKavett to the mouth of the river show a gradual gain over a 98 mile reach and a loss at the mouth of the river from 55.4 cubic feet per second (cfs) to 23 cfs (mile 105).

Holland and Mendieta (1965) investigated the baseflow of the Llano River system along a 83.5 mile reach from Junction (Kimble County) to Llano (Llano County) during January 1962. They found that most of the baseflow of the Llano River system is derived from springs on the two forks above Junction and from tributary infow. The springs emit from the base of the Edwards Group. Holland and Mendieta (1965) indicate that the river reach receives enough ground-water effluent possibly from alluvial deposits on the river channel and flood plain, directly to the channel, to make up all losses from the channel. Findings from 1918 and 1925 data are in agreement with 1962; 1952 data show a losing river, however, due to extreme drought conditions.

The recharge, flow, and discharge of these aquifers is controlled and/or modified to a large extent by the compartmentalization of the aquifers by the complicated system of faulting throughout the region (see Structure Section above). Several recent studies have addressed at least part of the problems or questions which may be due to this. The following are summaries of some of these reports.

Black (1988) in a study of the Hickory aquifer in Concho, McCulloch, and Mason counties, states : Simple radial flow outward from the outcrop is not indicated by the hydrogeologic data which imply fault-impeded flow through a significantly reduced area into the subsurface portions of the aquifer. This is a result of the complex flow patterns caused by the faulting.

In a study on the Katemcy Creek basin in Mason and McCulloch counties, Delaney (1990) inferred anomalously steep gradients to be associated with faults that impede ground-water flow across them. Anomalous ground-water flow directions were also inferred to be associated with faults.

Pettigrew's (1991) study of the Hickory in San Saba and parts of Mason and Llano counties also shows the influence faulting has on determining ground-water flow direction.

A study of the Hickory aquifer in Mason and McCulloch counties by Randolph (1991) concluded that observed spacial and temporal variation of water levels in wells show that faults impede lateral flow of ground water and influence the short- and long-term hydraulic responses of aquifers in fault defined regions.

Hydraulic Characteristics of Aquifers

Certain physical characteristics of aquifers help determine the amount of water in storage and the quantity and rate of yield to wells producing from an aquifer. These are collectively called the aquifer's hydraulic characteristics and include the coefficients of porosity, permeability, storage, and Transmissivity. Other measures which are important in describing aquifers and their ability to supply water to wells are yield and/or production rate, specific yield, and specific capacity (gallons per minute for foot of drawdown).

These parameters can be determined, or at least approximated, by conducting controlled pumping tests (aquifer tests) of wells. These tests are very expensive and time consuming, however, and interpretation is often difficult. Since these coefficients are a measure of an aquifer's ability to store and transmit water, they can be used to determine proper well spacing, measure or estimate interference between pumping wells, and to predict water-level drawdowns around pumping wells. Calculation or estimation of these parameters and their variability both horizontally and vertically through aquifers is essential in constructing a workable aquifer model. In all aquifers, these parameters are highly variable. Representative ranges of aquifer characteristics for the aquifers considered in this study are included in Table 4. The data included come from Board well records and pumping tests conducted by the Board, the USGS., water-well drillers, and others. Some of the data was selected from that presented in Alexander and others, (1964), Ashworth (1983), Brune and Duffin (1983), Follett (1973), Guyton (1973), Meyers (1969), Mount (1963), Mount and others (1967), Reeves (1967), Reeves (1969), Sieh (1975), Walker (1979), and Bluntzer (1992). While most of the data for the Paleozoic aquifers is from the study area, some of that for the Trinity and Plateau aquifers is from adjacent areas. It should be representative of that of the aquifer in the study area, however. Because of the nonhomogeniety of most aquifers, calculations of the hydraulic characteristics of any aquifer have to be considered with a grain of salt. In a sense, they are only very rough estimates of even the actual column of an aquifer (the well itself) on which they have been calculated, and should be expanded for use in regional studies very cautiously. Irregularities in well construction or lack of knowledge of the well's construction can cause wide variations in the final calculations of these parameters. This is all especially true of carbonate aquifers. In these aquifers the water occurs in fracture or solution-formed or -enlarged openings which are not uniform and which vary erratically in size and distribution . Since many of these solution openings are associated with faults and fractures, water movement in these aquifers is often unidirectional, at least locally. Because of these factors, quantitative determinations of storage and yield of carbonate aquifers are at best rough approximations and should be used with even more caution than those determined for sand aquifers (Bluntzer, 1992). Therefore, while these estimates can be used for ground-water flow modelling, care should be taken to keep the limitations of the "answers" and evaluations in perspective.

The parameter values, such as those summarized on Table 4, are generally calculated from pumping tests conducted on wells of known and acceptable construction. Rarely are complete aquifer tests run on low-production or really inefficiently constructed wells. Therefore the low figures for the aquifer characteristics ranges on Table 4 do not really represent the actual low for any of these aquifers. If fact, they are probably skewed significantly to the high side. The Table indicates a transmissibility of 126,000 gpd/ft for the San Saba part of the Ellenburger-San Saba aquifer and a range of 56,000 to 96,000 for the Ellenburger. Obviously in some parts of these formations the transmissibility is considerably lower than this. The permeability range for the Ellenburger, 550-678 gpd/ft^2, also does not represent the actual low end of the spectrum for this aquifer which would probably approach zero. This is also true to a lesser extent in the ranges of other aquifers. The characteristics of all aquifers are extremely variable over even very short distances, making the quantitative determination of yield and storage ranges very difficult. From Table 4, it is easy to see, that at least in general, the Hickory, Ellenburger-San Saba, and Edwards aquifers should be much more productive than the other area aquifers.

Construction of Wells

Well construction methods used within the study area are similar to those in use throughout the rest of Texas and the world (See Figure 13). However, open-hole completions like those illustrated in several of the wells shown on Figure 18 are much more common here than in most other areas. Such wells are not common in much of the State, because of problems in pumping sand and/or probable caving in uncased or unscreened wells. Because of the nature of the geologic formations in this area, mostly limestones, dolomites, and sands which are at least semiconsolidated, uncased wells have historically been constructed due to their lower cost. Over time, some of

Table 4. **Approximate range in representative hydraulic characteristics of the Paleozoic and Cretaceous aquifers**

Aquifer	Geological Units	Laboratory Porosity of Core (% Volume)	Approximate Results Determined From Pumping			
				Coef. of Storage (dimensionless)	Permeability (gpd/ft^2)	Transmissibility (gpd/ft)
Hickory	Hickory Sandstone Member	3 - 42		0.0001 - 0.00004	38 - 1,038	5, 000 - 44,000
Ellenburger - San Saba	San Saba Limestone Member	1 - 8		–	–	126,000
Ellenburger Group	1 - 17	0.0022		550 - 678	56,000 - 96,000	
Lower Trinity	Hosston Sand and Sligo Limestone Members	1-17		0.000022 - 0.00005	5 - 268	105 - 25,000
Middle Trinity	Cow Creek Limestone Member	5 - 38		–	49	3,300
Middle Trinity	Hensell Sand Member	11 - 34		0.0000008 - 0.00005	5 - 9	600 - 1,100
Middle Trinity	Lower Unit - Glen Rose Formation	9 - 28		0.000002	47 - 115	700 - 9,300
Upper Trinity	Upper Unit Glen Rose Formation	3 - 20		–	–	1,500
Edwards (Balcones Fault Zone)	Edwards Formation	3 - 26		0.0004 - 0.020	4 - 877	1,900 - 386,000

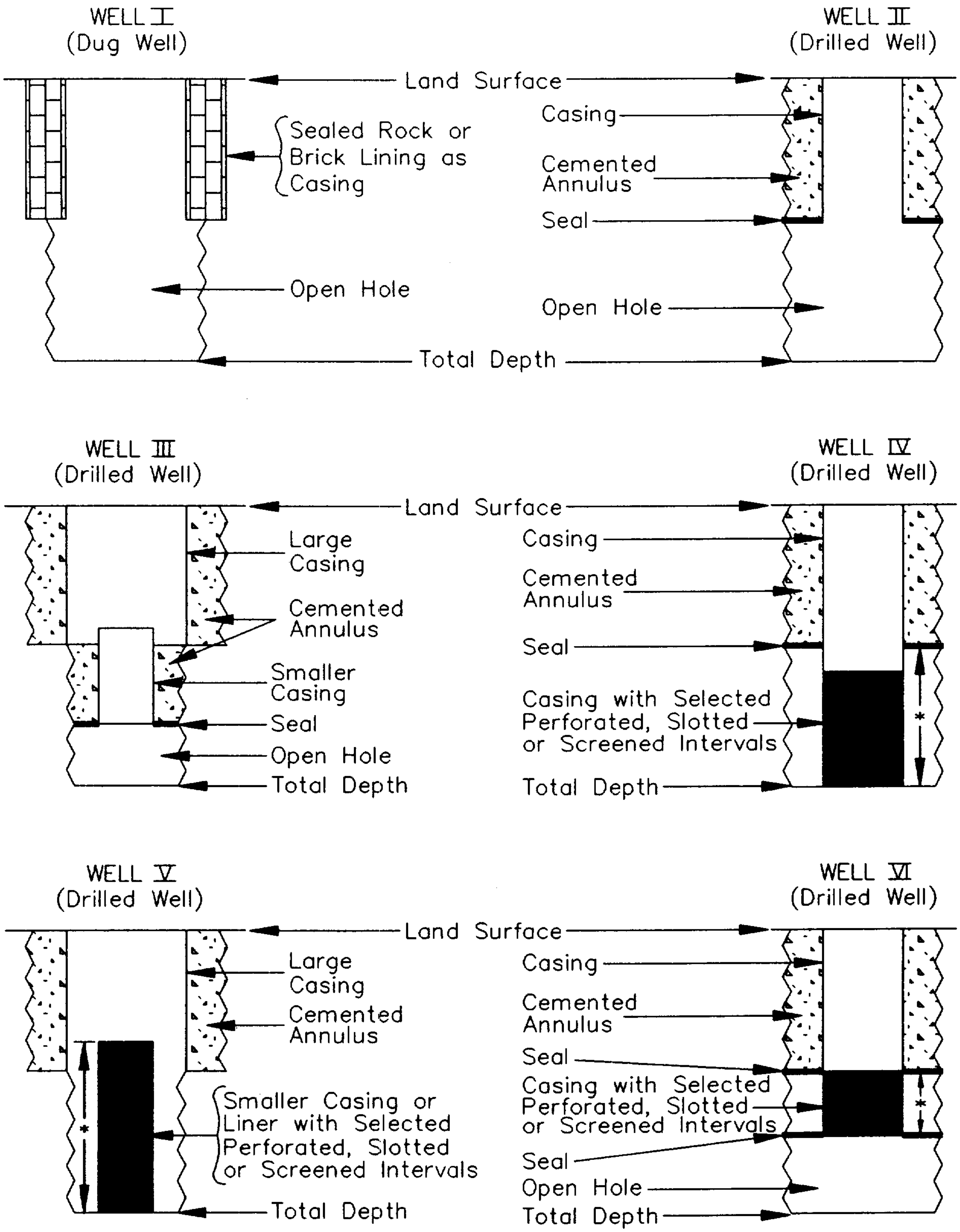


Figure 13. — Diagrams showing basic types of well construction used in the study area

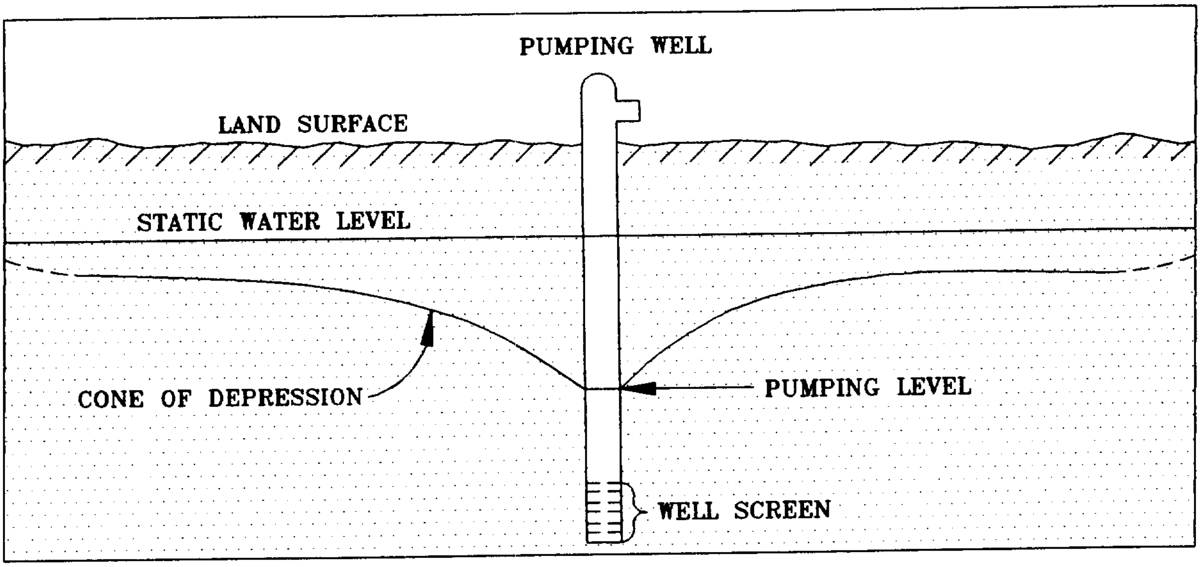
these wells completed in the Hickory Sand have shown a tendency to pump sand, causing several problems, including pump failure and caving of the well bore. The major purpose of good well construction is to insure that an adequate, or in most cases, a maximum amount of water moves into the well bore and thence through the pump to the surface, but without damage to the formation or the well. To make this happen in sand aquifers, the speed of the water when it leaves the formation must be kept below the point where the movement of the water will continue to move sand from the formation into the well. This calls for at least three things to make the most efficient well; a proper amount of opening in the screen, the proper size of pump, and proper well development. Proper well development will remove both drilling mud which has infiltrated the formation and the finer sand and silt from the part of the producing formation in the immediate vicinity of the well bore. In sand aquifers underreaming and gravel packing (with properly sized sand or gravel) will facilitate this procedure.

To insure more efficient, longer lasting wells, each new well should be constructed in the following manner: (1) a test hole should be drilled and logged to find the most productive interval or intervals; (2) the test hole should be reamed down to just above the selected producing zone(s); (3) surface casing should be set and cement grouted into place; (4) the proposed producing interval should be underreamed; (5)a screen should be selected with the optimum slot size to fit the sand sizes in the aquifer (in a sand aquifer) and/or the gravel-pack medium; (6) the underreamed interval should be gravel packed with gravel or sand also selected to fit the sand size; (7) the well should be developed and test pumped to determine the optimum pumping rate; and (8) a pump selected and placed in the well. In addition, some existing wells can be renovated, including screening and gravel packing, and made more efficient. These wells can be reworked or renovated if the bore size and/or surface casing size are large enough to work through. Decisions about renovating a well should be considered carefully, however, since such an operation is expensive, possibly costing as much as drilling a new properly-constructed well. In some cases, especially in well consolidated rock some of these steps may be unnecessary.

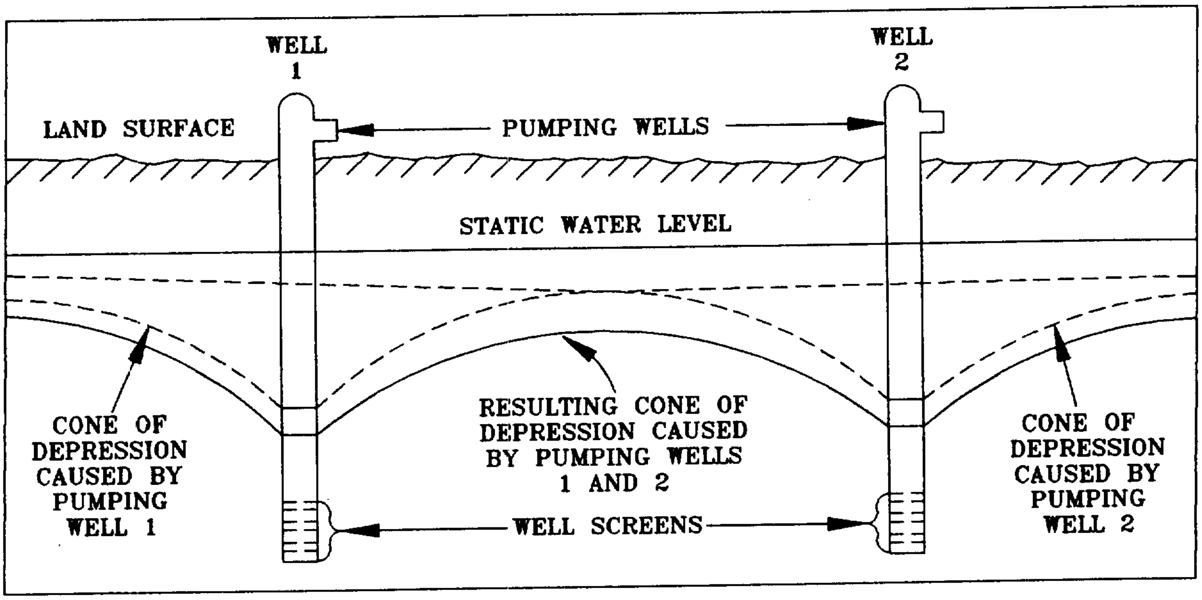
Water-Level Changes

Water-level changes in aquifers are due to many causes, some may be extremely local, but others are of great regional significance. Changes in recharge to or discharge from an aquifer are the most significant causes of water-level fluctuations. When drought conditions reduce recharge to an aquifer, some of the water discharged may come from storage and the water levels will decline. In time water levels may be lowered sufficiently to dry up springs or shallow wells. When rainfall resumes, the water removed during the drought may be replaced and water levels rise. In most aquifers there is a constant rebalancing of the forces of recharge and withdrawal and the water table and/or potentiometric surface is moving up and down in an often cyclic manner. There are cycles of pumpage, recharge, drought, season, etc., all working together in effecting the aquifer.

When a water well is pumped, water levels in the vicinity are drawn down in the shape of an inverted cone with its apex at the pumped well. This "cone of depression" is illustrated in diagram A of Figure 14. The development of this cone depends on the aquifer's coefficients of transmissivity and storage, and the rate of pumping. As pumping continues, the cone expands and continues to do so until it intercepts a source of replenishment capable of supplying sufficient water to satisfy the pumping demand. This source can be either intercepted natural discharge or induced recharge. If the quantity of water received from these sources is sufficient to compensate for the water pumped, the growth of the cone will cease and a balance between recharge and discharge is achieved. In areas where recharge or salvageable natural discharge is less than the amount of water pumped from wells, water continues to be removed from storage in the aquifer to supply the deficiency and water levels will continue to decline. This condition is often called "mining."



A. Cone of depression from water-level drawdown around a pumping well.



B. Added cone of depression effects from interference between two pumping wells

Figure 14. – Drawdown in water-levels around pumped wells

Where intensive development has taken place in ground-water reservoirs, each well superimposes its own individual cone of depression on the cone of neighboring wells. This results in the development of a regional cone of depression. When the cone of one well overlaps the cone of another, interference occurs and an additional lowering of water levels occurs as the wells compete for water by expanding their cones of depression. The amount or extent of interference depends on the rate of pumping from each well, the spacing between wells, the length time of pumping, and the hydraulic characteristics of the aquifer in which the wells are completed. The effects of interference between pumping wells are illustrated in diagram B on Figure 14.

Water levels in some wells, especially those completed in artesian aquifers, have been known to fluctuate in response to such phenomena as changes in barometric pressure, tidal force, earthquakes, and even passing railroad trains. However the magnitude of such fluctuations is usually quite small.

Water levels in the Paleozoic aquifers vary greatly within the study area. They are above the land surface in a few flowing wells and springs and are more than 400 feet below the land surface in some Hickory and Ellenburger-San Saba wells far downdip. Significant water-level declines have occurred within the aquifers, especially in the Hickory and Ellenburger-San Saba aquifers. As would be expected, the areas of greatest decline are in areas with the greatest ground-water pumpage. The most obvious of these is the large area of irrigation pumpage on the outcrop of the Hickory Sand in northeast Mason, northwest Llano, and southeast McCulloch counties. Figure 15 is a hydrograph of the 1974-1994 water-level measurements in well 56-06-614, a Hickory well located within this area. It shows not only the yearly cycle of rise and fall of the water table due to seasonable changes in recharge and pumpage, but a relatively steady decline in the water table over the measurement period. The highs in each yearly cycle, which more or less represent the static water level for this well and the area around the well, occur in April or May, just before the major irrigation pumping season starts. This static level declined about 19.5 feet between 1975 and 1994. The lowest measurement in each cycle is at the end of the irrigation season and represents a yearly maximum drawdown level for this well, perhaps approximating the pumping level of active wells in this immediate area. These yearly low levels have declined about 21.5 feet during the same period. Between 1943 and 1982, the water level in one of the City of Brady's older Hickory wells varied from a high of 117.5 feet below the land surface in November of 1943 to a low of 211.9 feet in July of 1971. In much of the study area, however, there has not been a steady decline of water levels in wells. Water levels in many wells have shown erratic patterns of decline and recovery, but, in general have remained comparatively static over their measuring periods, some of which go back at least 20 years. Figure 16 shows such a well in San Saba County (Well 41-51-404, Marble Falls aquifer), while Figure 17 represents data from a well in Gillespie County (Well 57-50-108, Ellenburger aquifer). Figures 18 and 19 represent wells in Mason County (Figure 18 is Well 56-06-611, Hickory aquifer and Figure 19 is Well 56-06-613, Hickory aquifer.

A part of the decline in these aquifers may be due to the effects of compartmentilization of the aquifers by faulting, (see the Structure Section of this report).

All of these effects of fault compartmentalization, as summarized in the Recharge, Movement, and Discharge Section above, would tend to cause water levels measured in even quite nearby wells to show significant variation, with pumping in one compartment delineated by the faulting often not having any or at most a reduced effect, on wells in another compartment. Pumpage from wells within the same compartment might effect water their water levels significantly more than if the faulting did not exist, however. The flow of ground water in unexpected directions can also be attributed to the effects of the faulting.

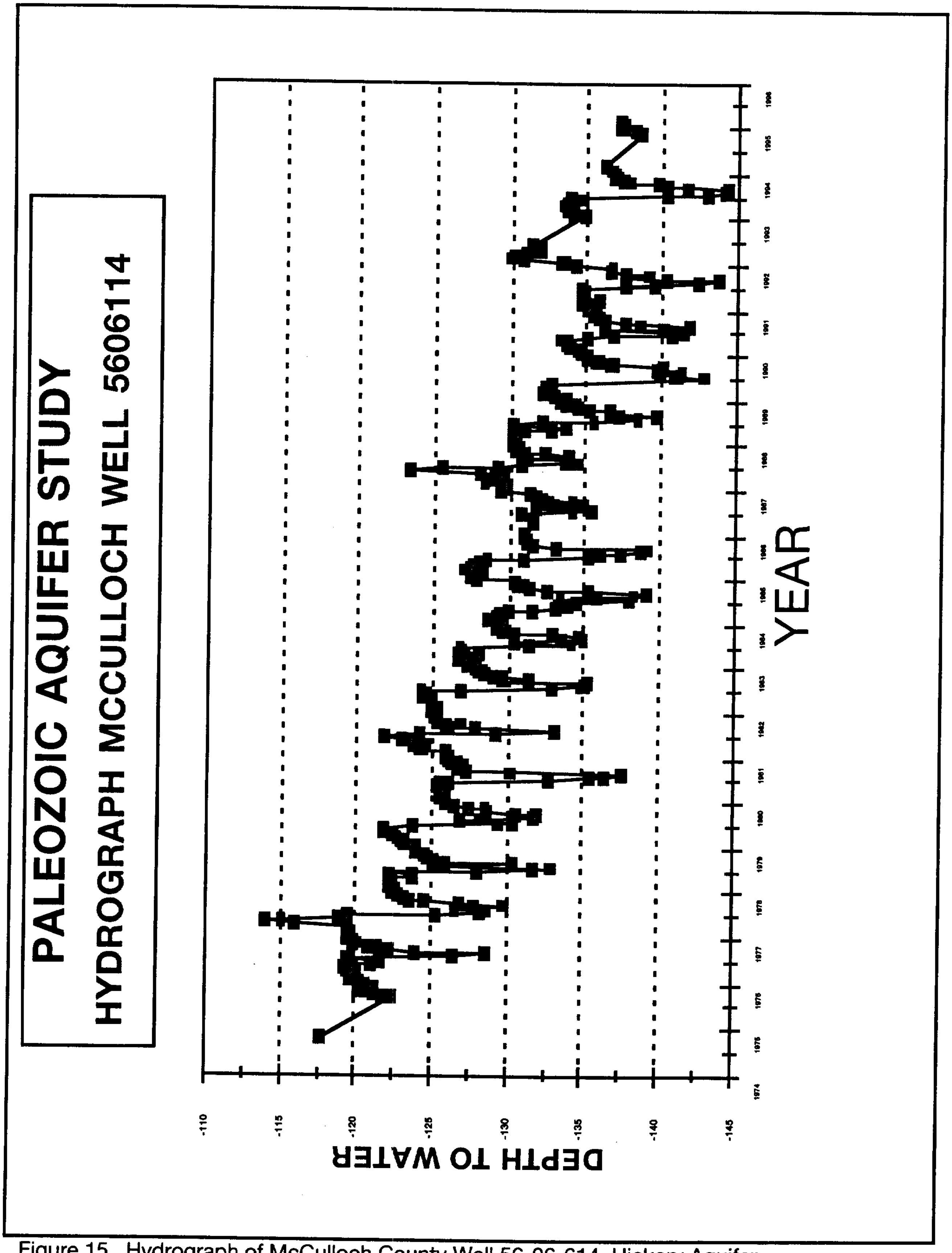


Figure 15. Hydrograph of McCulloch County Well 56-06-614, Hickory Aquifer

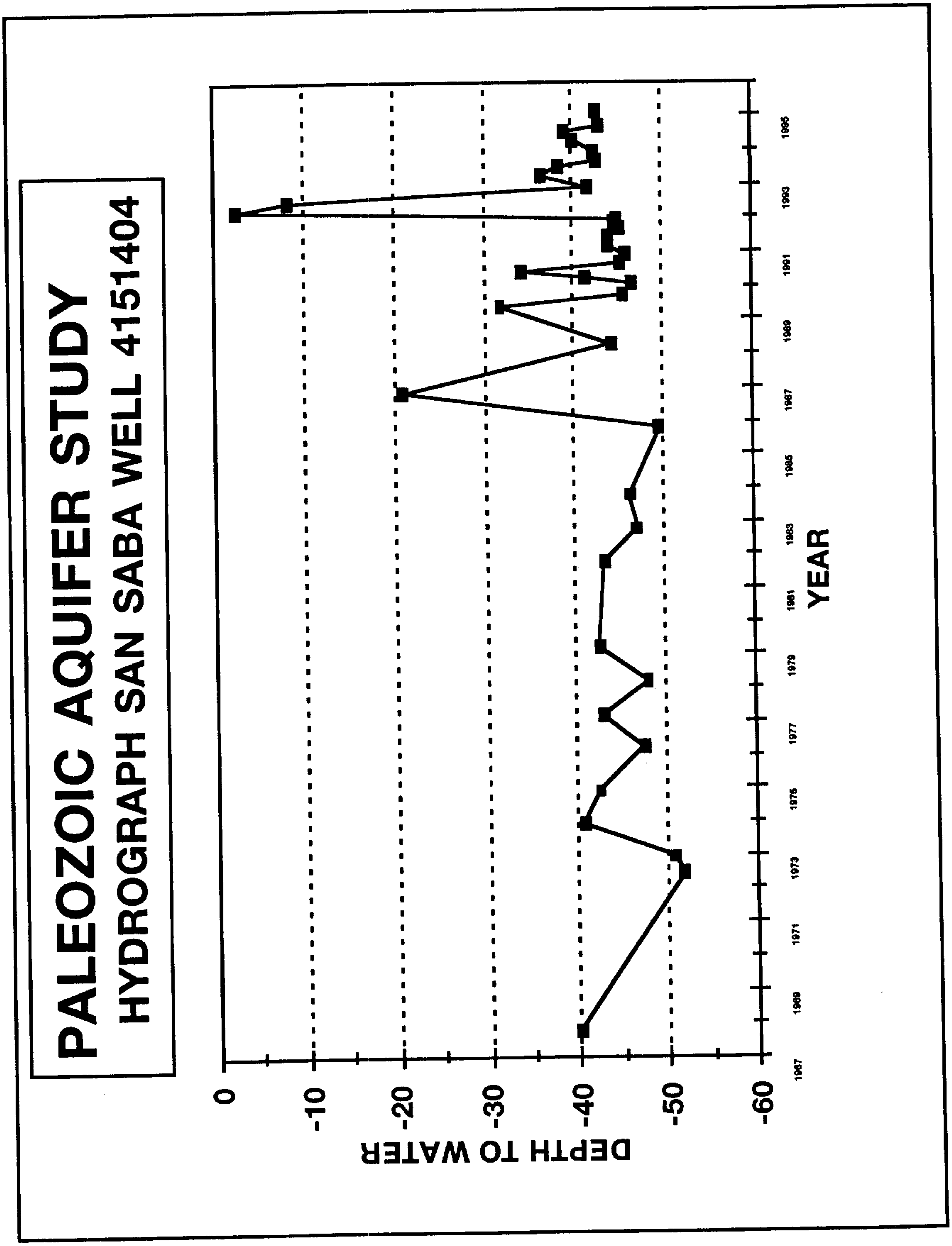


Figure 16. Hydrograph of San Saba County Well 41-51-404, Marble Falls Aquifer

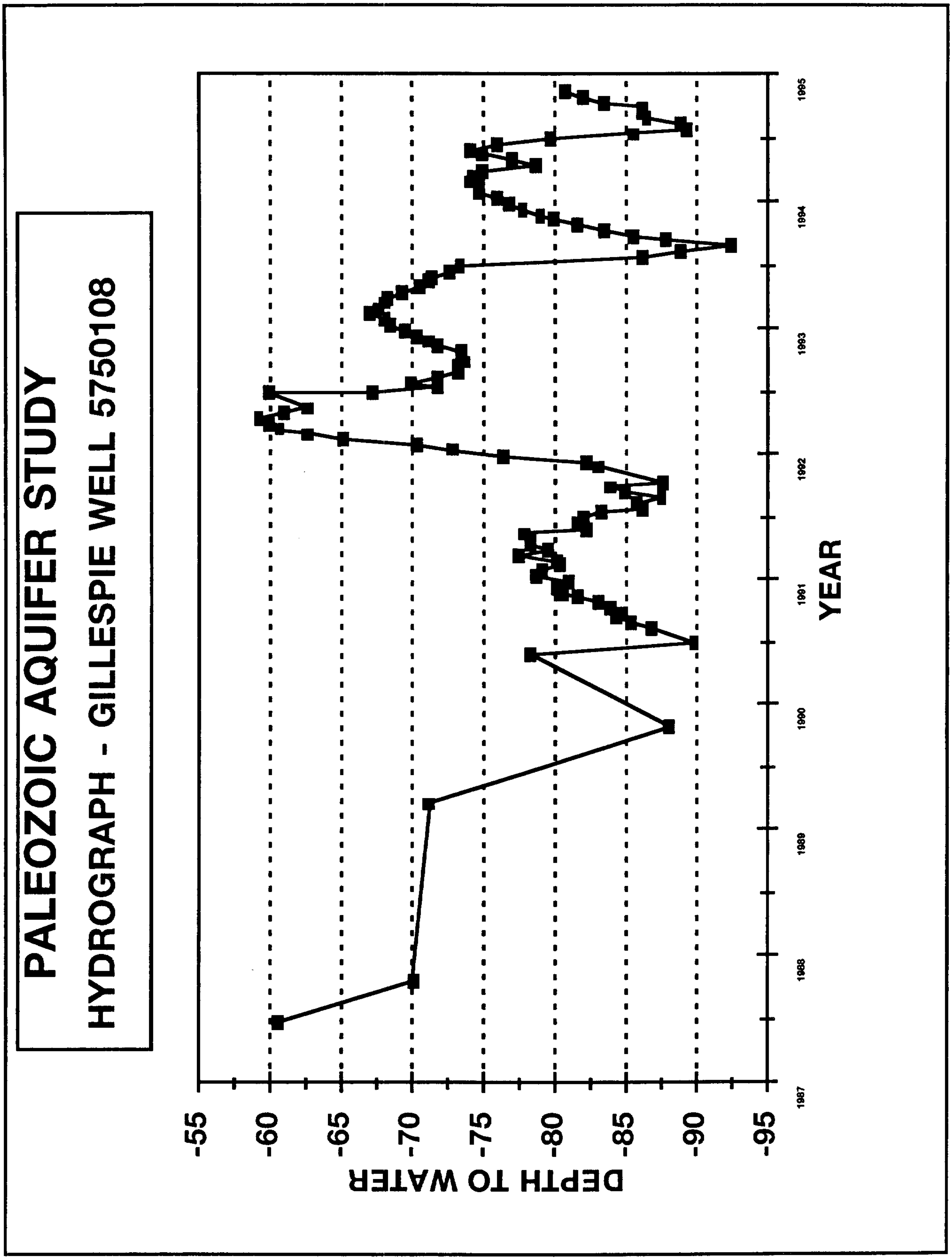


Figure 17. Hydrograph of Gillespie County Well 57-50-108, Ellenburger Aquifer

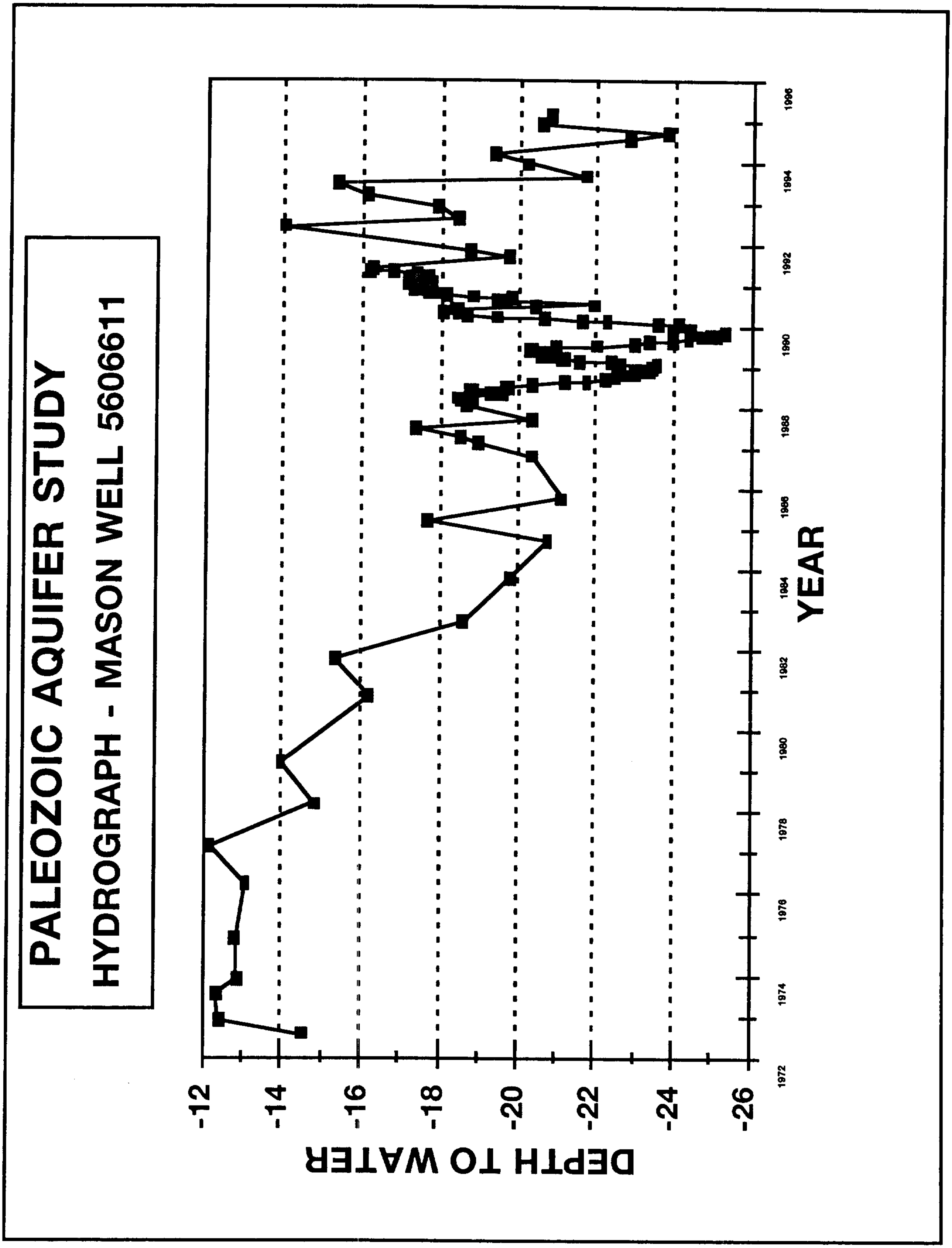


Figure 18. Hydrograph of Mason County Well 56-06-611, Hickory Aquifer

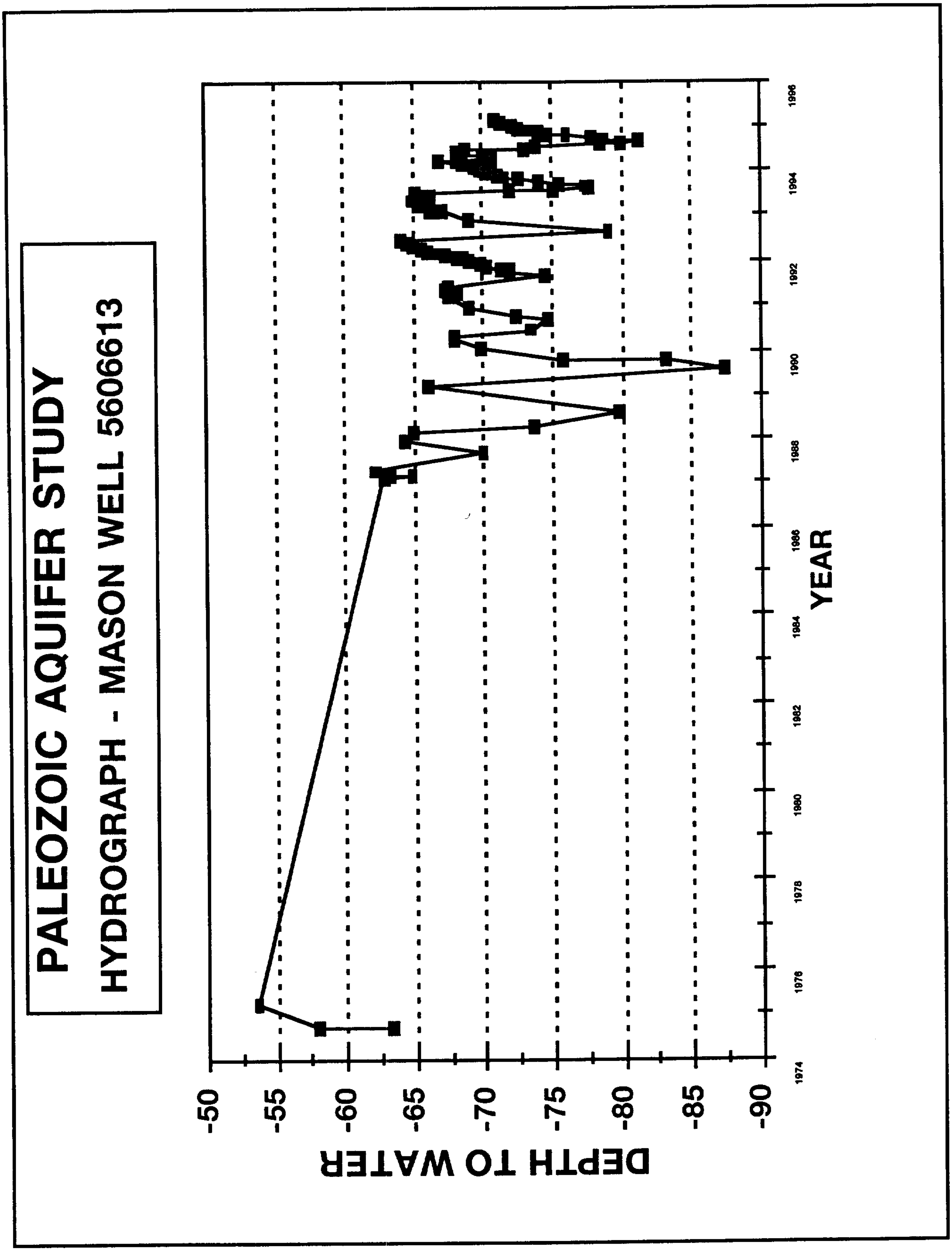
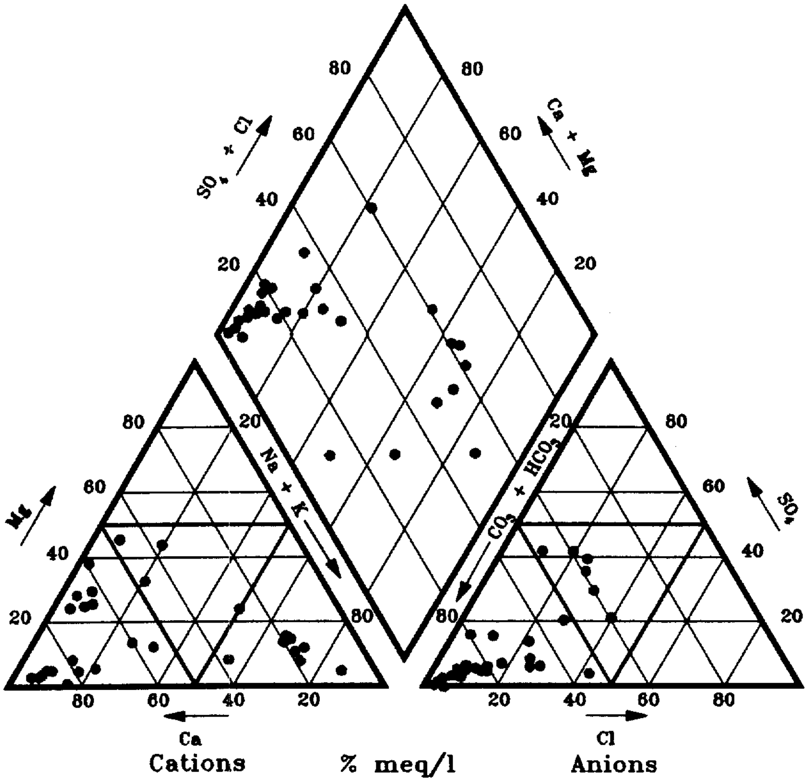
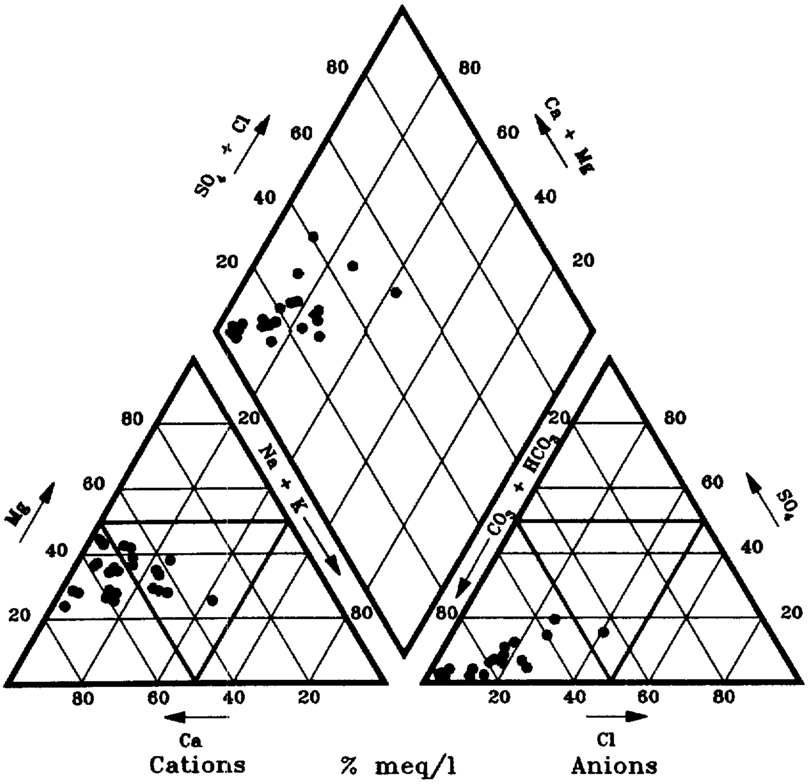


Figure 19. Hydrograph of Mason County Well 56-06-613, Hickory Aquifer

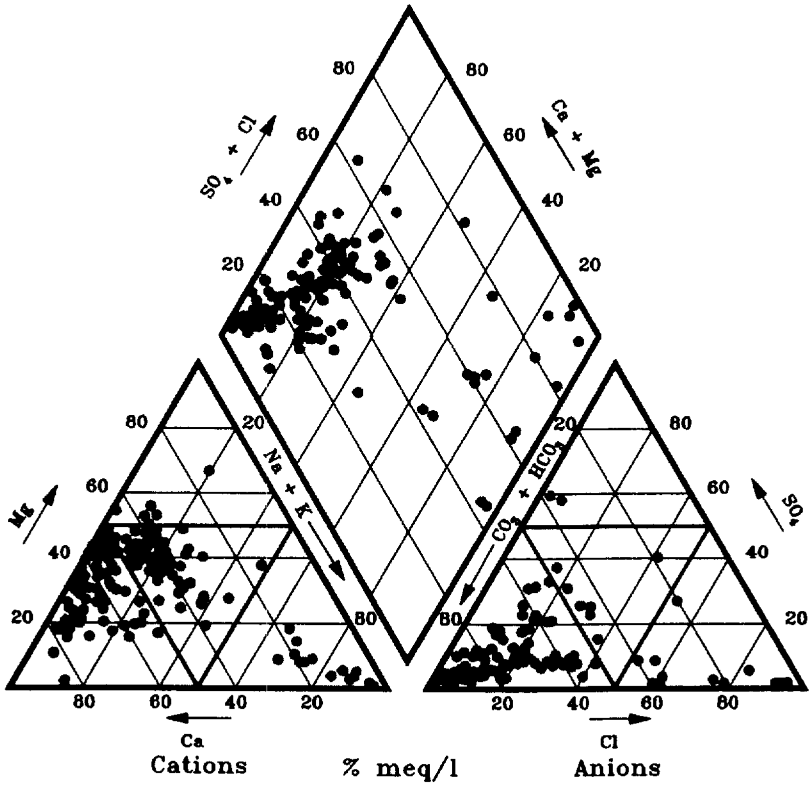


(A) Marble Falls

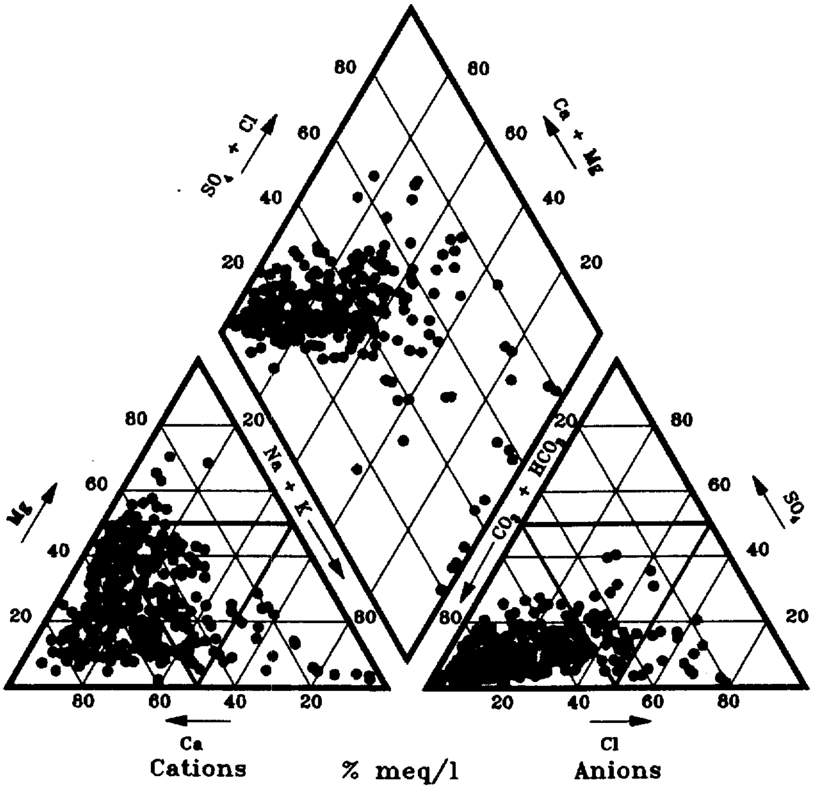


(B) San Saba

Figure 20. – Trilinear diagrams of ground water from the Marble Falls aquifer (A) and the San Saba Member, Ellenburger–San Saba aquifer (B).



(A) Ellenburger



(B) Hickory

Figure 21. – Trilinear diagrams of ground water from the Ellenburger Group, Ellenburger–San Saba aquifer (A) and the Hickory aquifer (B).

Table 5. Constituents and properties of ground water from the Marble Falls aquifer.

Constituents and properties *(number of samples)*	Average	Range
silica (mg/l) (36)	12	15 - 17
calcium (mg/l) (36)	97	28 - 188
magnesium (mg/l) (36)	23	2 - 62
sodium (mg/l) (36)	66	2 - 381
potassium (mg/l) (36)	5.0	0.1 - 32.0
strontium (mg/l) (36)	-	-
bicarbonate (mg/l) (36)	404	276 - 572
sulfate (mg/l) (36)	65	4 - 261
chloride (mg/l) (36)	-	-
fluoride (mg/l) (36)	0.7	0.1 - 3.9
nitrate (mg/l) (36)	15.3	0 - 42.5
total dissolved solids(mg/l)	529	324 - 1106
total hardness (mg/l) (36)	335	133 - 519
gross alpha (pCi/l) (5)	4.0	2.5 - 5.3
gross beta (pCi/l) (2)	7.3	6.3 - 8.2
radium-226 (pCi/l) (0)	-	-
radium-228 (pCi/l) (0)	-	-

Table 6. Constituents and properties of ground water from the Ellenburger Group, Ellenburger-San Saba aqufier.

Constituents and properties *(number of samples)*	Average	Range
silica (mg/l) (215)	13	1 - 32
calcium (mg/l) (215)	90	2 - 276
magnesium (mg/l) (215)	37	1 - 109
sodium (mg/l) (215)	70	0 - 2360
potassium (mg/l) (215)	4.4	0.1 - 32.0
strontium (mg/l) (215)	6.0	0.1 - 25.7
bicarbonate (mg/l) (215)	400	0 - 600
sulfate (mg/l) (215)	43	4 - 725
chloride (mg/l) (215)	104	6 - 3760
fluoride (mg/l) (215)	0.7	0 - 8.2
nitrate (mg/l) (215)	10.4	0 - 50.0
total dissolved solids(mg/l)	568	307 - 6486
total hardness (mg/l) (215)	376	8 - 997
gross alpha (pCi/l) (23)	7.4	2.0 - 30.0
gross beta (pCi/l) (8)	18.3	4.1 - 41.0
radium-226 (pCi/l) (5)	3.7	0.2 - 8.0
radium-228 (pCi/l) (5)	8.0	2.1 - 19.0

Table 7. Constituents and properties of ground water from the San Saba Member, Ellenburger - San Saba aquifer.

Constituents and properties *(number of samples)*	**Average**	**Range**
silica (mg/l) (35)	14	7 - 34
calcium (mg/l) (35)	99	60 - 147
magnesium (mg/l) (35)	46	26 - 83
sodium (mg/l) (35)	36	5 - 160
potassium (mg/l) (35)	3.2	0.1 - 15.0
strontium (mg/l) (35)	-	
bicarbonate (mg/l) (35)	452	347 - 509
sulfate (mg/l) (35)	38	8 - 136
chloride (mg/l) (35)	53	7 - 229
fluoride (mg/l) (35)	0.3	0.1 - 0.9
nitrate (mg/l) (35)	7.9	2.9 - 14.6
total dissolved solids(mg/l)	541	358 - 968
total hardness (mg/l) (35)	436	338 - 700
gross alpha (pCi/l) (0)	-	-
gross beta (pCi/l) (0)	-	-
radium-226 (pCi/l) (0)	-	-
radium-228 (pCi/l) (0	-	-

Table 8. Constituents and properties of ground water from the Welge Sandstone Member, Mid-Cambrian aquifer.

Constituents and properties *(number of samples)*	**Average**	**Range**
silica (mg/l) (17)	18	10 - 32
calcium (mg/l) (17)	86	50 - 152
magnesium (mg/l) (17)	41	9 - 57
sodium (mg/l) (17)	36	2 - 95
potassium (mg/l) (17)	6.6	0.2 - 13.0
strontium (mg/l) (17)	1.3	0.3 - 2.2
bicarbonate (mg/l) (17)	420	339 - 572
sulfate (mg/l (17)	41	21 - 103
chloride (mg/l) (17)	43	6 - 141
fluoride (mg/l) (17)	0.7	0.3 - 1.3
nitrate (mg/l) (17)	19.6	0 - 60.1
total dissolved solids(mg/l)	494	319 - 670
total hardness (mg/l) (17)	384	240 - 518
gross alpha (pCi/l) (8)	10.9	2.5 - 24.0
gross beta (pCi/l) (4)	17.7	8.8 - 31.0
radium-226 (pCi/l) (3)	4.5	3.4 - 5.9
radium-228 (pCi/l) (3)	4.9	3.0 - 7.3

Table 9. Constituents and properties of ground water from the Mid-Cambrian aquifer.

Constituents and properties *(number of samples)*	Average	Range
silica (mg/l) (14)	14	11 - 29
calcium (mg/l) (14)	72	54 - 116
magnesium (mg/l) (14)	28	15 - 49
sodium (mg/l) (14)	19	12 - 28
potassium (mg/l) (14)	5.0	0.2 - 11.0
strontium (mg/l) (14)	-	-
bicarbonate (mg/l) (14)	358	228 - 461
sulfate (mg/l) (14)	23	17 - 41
chloride (mg/l) (14)	17	6 - 26
fluoride (mg/l) (14)	0.7	0.3 - 0.9
nitrate (mg/l) (14)	0.2	0 - 1.0
total dissolved solids(mg/l)	494	319 - 670
total hardness (mg/l) (14)	296	233 - 372
gross alpha (pCi/l) (8)	25.5	2.9 - 82.0
gross beta (pCi/l) (6)	21.2	5.9 - 45.0
radium-226 (pCi/l) (2)	12.6	2.1 - 23.0
radium-228 (pCi/l) (2)	2.4	1.2 - 3.6

Table 10. Constituents and properties of ground water from the Hickory aqufer.

Constituents and properties *(number of samples)*	Average	Range
silica (mg/l) (620)	18	0 - 47
calcium (mg/l) (620)	67	1 - 246
magnesium (mg/l) (620)	25	1 - 95
sodium (mg/l) (620)	53	0 - 740
potassium (mg/l) (620)	6	0 - 35
strontium (mg/l) (620)	0.9	0.1 - 3.1
bicarbonate (mg/l) (620)	307	53 - 683
sulfate (mg/l) (620)	39	0 - 327
chloride (mg/l) (620)	62	4 - 920
fluoride (mg/l) (620)	0.9	0.1 - 9.2
nitrate (mg/l) (620)	10.3	0 - 78
total dissolved solids(mg/l)	427	114 - 1941
total hardness (mg/l) (620)	270	6 - 820
gross alpha (pCi/l) (105)	18.0	2.1 - 73.4
gross beta (pCi/l) (38)	33.6	1.0 - 124.0
radium-226 (pCi/l) (65)	3.9	0.3 - 14.0
radium-228 (pCi/l) (60)	11.0	1.1 - 55.0

in other words, the concentration should be less than this limit]. In the study area, nitrate and radioactivity exceed maximum contamination levels in isolated instances in almost all of the aquifers sampled.

The maximum contamination level for nitrate is 44.3 mg/l as nitrate (NO3) (this is equal to about 10 mg/l as nitrogen). This value is exceeded in some isolated wells in the Marble Falls aquifer, the Ellenburger Group, Ellenburger-San Saba aquifer, the Welge Sandstone Member, Mid-Cambrian aquifer and the Hickory aquifer. Excessive nitrate in urbanized areas is probably due to septic tank discharges and lawn fertilizers, while excessive nitrate in rural areas is attributed to animal waste and/or septic tank discharge (see Appendix A). Nitrate contamination often occurs in shallow aquifers and where inadequate well completion techniques allow contaminated water to run down the well bore.

With a maximum contamination level of 15 pCi/l, gross alpha concentrations are exceeded in some wells in the Mid-Cambrian and the Hickory aquifers. The maximum contamination level for both Radium-226 and Radium-228 combined is 5 pCi/l. Radium-226 and Radium-228 exceed acceptable levels in some wells in the Ellenburger-San Saba, Mid-Cambrian, andHickory aquifers. Cech, et al (1988) found that in 15 samples taken from the Hickory and Ellenburger-San Saba aquifers in Concho, McCulloch and San Saba counties, radon concentrations varied from less than 100 up to 1,400 pCi/l with a median concentration of 200 pCi/l. The maximum contamination level for radon-222 is 300 pCi/l. The source of radioactivity is from uranium and thorium in the Paleozoic shales and sandstones of the study area and from PreCambrian igneous and metamorphic rocks (see Appendix A). HDR (1991) discussed the use of sodium cation exchange treatment to reduce concentrations of radium and radon in water from the Hickory aquifer in Concho, McCulloch and San Saba counties.

GROUND-WATER AVAILABILITY

Estimated Future Ground-Water Availability

The Board has historically made estimates of ground-water availability for the delineated aquifers of Texas. These estimates are revised as new data is accumulated and/or new studies are completed. A major part of this study was to evaluate the current availability estimates for the Hickory, Ellenburger-San Saba, and Marble Falls aquifers and refine them if possible. Also, an estimate was to be made of the availability of usable water from the Mid-Cambrian aquifer, since this aquifer has not formally been delineated as a minor aquifer by the Board. Ground-water availability estimates are made by the Board using several methods, depending on the type of aquifer and the amount and type of data available. Detailed explanations of the various methods can be found in TWDB Report 238 (Price and Muller, 1973). Board estimates of annual availability by county from each of the aquifers are included in Table 11. An evaluation of existing data on the Hickory, Ellenburger-San Saba, and Marble Falls aquifers resulted in a determination that due to the complexity of the rock framework and compartmentalization of these aquifers, the existing availability estimates could not be significantly improved. There is insufficient data available for the more detailed geologic and hydrologic mapping needed for good regional aquifer flow modeling and/or any of the other more sophisticated methods of estimation of water availability for these aquifers. In a recent TWDB study, however, Bluntzer (1992) made new determinations of the availability of ground water within the aquifers of several central Texas counties, which included Gillespie and Blanco counties from the present study. These determinations were made using Board estimates of recharge modified by consideration of recent ground-water pumpage within the counties along with any water-level changes. We have included Mr. Bluntzer's changes, and therefore the availability totals for these two counties and the total aquifer availabilities are different from previous published totals.

The annual availability of the Hickory, Ellenburger-San Saba, and Marble Falls aquifers has been estimated by the TWDB at the annual effective recharge. The annual effective recharge rates for each of these aquifers has been estimated, based on average rainfall, the areal extent of outcrop of each of the aquifers, and the amount, extent, and position of faulting associated with the aquifers. These estimates have been confirmed wherever possible by comparisons of the amounts of water pumped from the aquifers and the resultant water-level changes. The historical response of the water table as compared with total yearly pumpage for each aquifer was also considered, especially for the Ellenburger-San Saba aquifer. For the Hickory aquifer this estimated amount was originally 52,600 acrefeet per year, but with the changes for Gillespie and Blanco counties is now 46,149 acrefeet per year (the original estimate was calculated using 10 percent of the average annual precipitation and a more precise outcrop area determined from newer-more detailed geologic maps and using a planimeter); for the Ellenburger-San Saba aquifer, the earlier estimate was 29,400 acrefeet per year but is now 34,912 (the original figure is based on spring flow estimates of Barnes, 1975; about 2 percent of the average annual precipitation would support this total); and for the Marble Falls aquifer, 26,400 acrefeet per year (also based on springflow estimates by Barnes, 1975; about 5 percent of the average annual precipitation would support this total).

The Mid-Cambrian aquifer was evaluated using the same methods (determination of the areal extent of the outcrop and the application of 3 percent of the average annual precipitation). This aquifer will probably never be officially delineated as a minor

Table 11. Annual water available frm area aquifers

Aquifer	Effective Recharge	Blanco	Burnet	Gillespie	Llano	McCulloch	Mason	San Saba	Kimble	Lampasas	Menard
Ellenburger - San Saba	34,912	4,600	3,736	4,000	900	4,271	4,200	12,106	256	654	189
Hickory	46,149	800	4,747	2,000	10,982	3,000	18,882	5,738	0	0	0
Marble Falls	26,400	300	5,625			3,912		12,380		4,183	
Mid-Cambrian	1,260	300	100	300	30	130	200	200			
Edwards-Trinity Plateau		100		1,400		4,456	2,359		26,734		19,133
Trinity		1,600	1,835	3,400		11				1,733	
Total		**7,700**	**16,043**	**11,100**	**11,912**	**15,769**	**25,641**	**30,424**	**26,990**	**6,570**	**19,322**

aquifer, since usage is small and it is of small areal extent. Because the sands of the Mid-Cambrian aquifer are relatively thin and the areal extent of their outcrops is small, the estimated average annual recharge of 1,260 acrefeet is relatively small.

The availability of surface water for future development within the study area is dependent on prior claims and existing water rights, including many senior downstream rights for municipal, industrial, and irrigation usage. There are few good sites for the construction of new surface water reservoirs in the area. Almost all if not all of the annual yield of the existing reservoirs and run of the river rights are taken. Most of the cities which currently use surface water for at least a part of their supply could probably secure additional rights through purchase of existing water rights.

Artificial Recharge

Todd (1980) defines artificial recharge as: augmenting the natural movement of surface water into underground formations by some method of construction, by spreading of water, or by artificially changing natural conditions. The two major methods of artificial recharge are surface spreading and injection wells (Pettyjohn, 1981). Surface spreading may involve flooding large areas of land, basin construction, excavation of ditches or modifying existing stream channels. Water is diverted to such catchment structures and allowed to infiltrate.

Injection wells allow the injection of a water source directly into a ground-water system. Aquifer storage and recovery (ASR) wells are combination recharge and pumping wells and are used for seasonal storage of water. They are used for recharge when surplus water is available, and pumped when water is in demand (Bouwer, 1994).

Both of these methods benefit from treatment of the source water for truly efficient operation. Basin infiltration methods are subject to siltation of the basins if the water is not allowed time for suspended silt and clay particles to settle before being placed in the basins. In injection wells, silt and clay may clog the pore spaces around the well bore or even the well screens if not removed prior to injection. Intrained air in the injected water may also cause problems. Many injections wells are pumped occasionally not only for reuse of the water, but to help clear out silt and clay plugging the aquifer around the wells.

The Hickory Underground Water Conservation District (HUGWCD), which covers parts of San Saba, McCulloch, Mason, Kimble, Menard and Concho counties, has considered the possibility of artificially recharging the Hickory aquifer by using retention dams and lakes in the Katemcy Creek Basin and on tributaries of the San Saba River [Bluntzer and Derton, 1988; Stan Reinhart (HUGWCD), personal communication, 1994]. The Hill Country Underground Water Conservation District (HCUGWCD), which covers Gillespie County, is considering the possibility of an aquifer storage and recovery project using combination recharge/production wells in the Hickory aquifer [Paul Tybor (HCUGWCD), personal communication, 1994].

HISTORICAL AND PROJECTED POPULATION AND WATER USE

Most of the statistical data included in this section is based on the seven core counties of the area, which includes Blanco, Burnet, Gillespie, Llano, McCulloch, Mason, and San Saba.

Historical Population

European settlement of this area began in the 1840s. By 1860, the U.S. census showed over 9,000 people within the core counties of the study area (Blanco, Burnet, Gillespie, Llano, McCulloch, Mason, and San Saba). Gillespie County was established in 1848, and most of the other counties were set up during the 1850s. As can be seen in Table 12, Historic Population by County, growth was slow but steady in most of the counties until 1890-1910. Between 1910 and 1920, almost all of the counties showed a significant decline in population, perhaps due to movements caused by World War I, including not only men into the armed forces, but whole families into the towns and larger cities to work in war-related industries. Table 13 shows the historic population of selected area cities by decade. From 1920 through some time between 1950 and 1960, most of the counties and some of the cities showed relatively significant population declines, perhaps reflecting the general migration of rural people to the larger metropolitan centers, in this case mostly to San Antonio and Austin. This decline was accelerated during World War II. A few of the counties, Mason and San Saba for instance, and several of the cities have continued to decline in population right up to the present. McCulloch County population has remained relatively constant since 1960, and Blanco, Gillespie, Burnet, and Llano counties have shown varying rates of growth during this period. In general, except for the decades of World War I (1910-1920) and World War II (1940-1950), the area has grown in population, at least within the seven core counties shown on Table 12. In 1994, as it has been since World War II, a large portion of the population is concentrated in and adjacent to the incorporated cities and towns as well as several unincorporated communities. The incorporated cities include Bertram (1990 population 849), Blanco (1,238), Brady (5,946), Burnet (3,504), Cottonwood Shores (548), Eden (1,567), Fredericksburg (6,934), Granite Shoals (1,378), Johnson City (932), Llano (2,962), Marble Falls (4,007), Mason (2,041), Meadowlakes (514), Melvin (184), Richland Springs (344), Round Mountain (59), Royal Oaks (NA), San Saba (2,626), Sunrise Beach (497), Unincorporated communities are mostly small and/or very diffuse in population, but some are quite large. Some of the larger include Buchanan Dam (1,038), Horseshoe Bay (1,546), and Kingsland (2,725).

Historical Water Use

Currently, ground water supplies much of the demand for all uses except power within most of the study area. Surface water use is relatively minor except for the municipal supply of the cities of Llano, Burnet, Marble Falls, and Johnson City; power generation at Buchanan Dam in Llano County; and some irrigation, especially in Gillespie and San Saba counties. The City of San Saba reports their water supply as surface water as a requirement of their permit with the Texas Natural Resource conservation Commission, but it is from springs and shallow wells drilled right at the springs, and, therefore, is actually ground water. Table 14 shows 1980, 1985, and 1990 water use by county and category, including municipal, manufacturing, power, mining, irrigation, and livestock supplies. This includes both ground and surface water. Table 15 shows the estimated pumpage of ground water by aquifer and category for the ten years available between 1980 and 1993. Table 16 shows a surface-water - ground-water breakdown of total reported water use for the seven core counties of the study area for the years 1980, 1985, and 1990.

Table 12. - Historic population by county - U.S. Census years

Historic Population by County								
Year	Blanco	Burnet	Gillespie	Llano	McCulloch	Mason	San Saba	Total
1850	0	0	1,240	0	0	0	0	1,240
1860	1,281	2,487	2,736	1,101	0	630	913	9,148
1870	1,187	3,688	3,566	1,379	173	678	1,425	12,096
1880	3,583	6,855	5,228	4,962	1,533	2,655	5,324	30,140
1890	4,649	10,747	7,056	6,772	3,217	5,180	6,641	44,262
1900	4,703	10,528	8,229	7,301	3,960	5,573	7,569	47,863
1910	4,311	10,755	9,447	6,520	13,415	5,683	11,245	61,376
1920	4,063	9,499	10,015	5,360	11,020	4,824	10,045	54,826
1930	3,842	10,355	11,020	5,538	13,883	5,511	10,273	60,422
1940	4,264	10,771	10,670	5,996	13,208	5,378	11,012	61,299
1950	3,780	10,356	10,520	5,377	11,701	4,945	8,666	55,345
1960	3,657	9,265	10,048	5,240	8,815	3,780	6,381	47,186
1970	3,567	11,420	10,553	6,979	8,571	3,356	5,540	49,986
1980	4,681	17,803	13,532	10,144	8,735	3,683	5,693	64,271
1990	5,972	22,677	17,204	11,631	8,778	3,423	5,401	75,086

Table 13. - Historic population in major area cities - U.S. Census years

Historic Population Major Area Cities						
Year	**Blanco**	**Brady**	**Burnet**	**Fredericksburg**	**Mason**	**San SabaA**
1910	—	2,669	981	—	—	—
1920	—	2,197	966	—	1,200	2,011
1930	—	3983	1,005	2,416	1,200	2,240
1940		5,002	1,945	3,544	1,500	2,927
1950	—	5,944	2,394	3,854	2,448	3,400
1960	—	5,338	2,394	4,629	1,815	2,728
1970	—	5,557	2,864	5,326	1,806	2,555
1980	—	5,969	3,410	6,412	2,153	2,336
1990	1,238	5,946	3,423	6,934	2,041	2,626

Table 14. Historical water use - by county and category for the years 1980, 1985, and 1990 ***(includes both ground and surface water - in acrefeet)***

County	Blanco			Burnet			Gillispie			Llano		
	1980	1985	1990	1980	1985	1990	1980	1985	1990	1980	1985	1990
Municipal	736	800	904	2,888	3,659	3,526	2,273	2,773	3,154	2,094	2,459	2,488
Manufacturing	1	0	0	94	12	1,116	585	273	451	93	4	0
Power	0	0	0	0	0	0	0	0	0	1,075	1,226	937
Irrigation	225	299	483	636	600	300	1,680	1,859	2,000	1,540	1,000	1,122
Mining	0	0	0	1,018	640	936	0	16	14	0	73	65
Livestock	474	426	553	625	900	820	1,161	912	1,056	785	822	908
Total	**1,436**	**1,525**	**1,940**	**5,261**	**5,822**	**6,698**	**5,699**	**5,833**	**6,675**	**5,587**	**5,584**	**5,520**

County	McCulloch			Mason			San Saba		
	1980	1985	1990	1980	1985	1990	1980	1985	1990
Municipal	2,637	2,385	2,636	728	741	723	1,260	1,168	1,272
Manufacturing	1,744	913	781	0	0	0	245	245	0
Power	0	0	0	0	0	0	0	0	0
Irrigation	2,850	3,570	2,071	16,050	16,509	17,747	10,050	12,366	5,734
Mining	0	128	118	0	0	0	0	96	86
Livestock	1,064	782	597	1,052	1,006	988	1,376	1,021	1,121
Total	**9,295**	**7,778**	**6,203**	**17,830**	**18,256**	**19,458**	**12,931**	**14,896**	**8,213**

Table 15. Estimated ground-water pumpage - Paleozoic aquifers - by aquifer and category *(in acre-feet)*

Paleozoic Aquifer Study - Estimated Ground-Water Pumpage

Ellenburger-San Saba

Category	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992
Municipal	3,702	2,985	2,598	3,569	3,505	3,071	3,256	3,216	3,146	3,136
Manufacturing	0	20	0	0	0	0	0	0	0	0
Power	0	0	0	0	0	0	0	0	0	0
Mining	0	155	17	18	15	117	174	174	92	134
Irrigation	8,600	2,186	1,726	1,476	635	337	2,125	1,903	2,081	2,084
Livestock	1,307	1,094	1,106	1,175	1,067	1,113	1,104	1,120	1,154	1,383
Total	**13,609**	**6,440**	**5,447**	**6,238**	**5,222**	**4,638**	**6,659**	**6,413**	**6,473**	**6,737**

Hickory

Category	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992
Municipal	5,263	4,146	4,018	3,664	3,846	3,866	4,149	4,087	3,905	3,972
Manufacturing	1,633	2,422	777	961	256	574	633	642	423	640
Power	0	0	0	0	0	0	0	0	0	0
Mining	0	160	224	234	196	279	269	269	461	461
Irrigation	19,921	18,263	22,316	20,900	19,394	21,985	22,180	20,505	20,920	14,675
Livestock	1,531	920	915	1,005	903	912	899	899	929	1,109
Total	**28,348**	**25,911**	**28,250**	**26,764**	**24,595**	**27,616**	**28,130**	**26,402**	**26,638**	**20,857**

Marble Falls

Category	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992
Municipal	804	405	260	288	240	300	3,304	341	291	306
Manufacturing	81	200	200	200	0	17	0	0	0	0
Power	0	0	0	0	0	0	0	0	0	0
Mining	0	32	0	1	0	0	0	0	0	0
Irrigation	238	213	355	119	138	111	170	109	109	0
Livestock	227	428	326	379	340	344	340	340	349	387
Total	**1,350**	**1,278**	**1,141**	**987**	**718**	**772**	**814**	**790**	**749**	**693**

Table 16. Historical ground-water – surface-water use, by county

County	Estimated Historical Ground-Water – Surface-Water Use (*in acre-feet*)											
	1980			1985			1990			1992		
	GW	SW	Total	GW	SW	Total	GW	SW	Total	GW	SW	Total
Blanco	886	550	1,436	1,085	440	1,525	1,514	426	1,940	1,617	469	2,086
Burnet	2,122	3,139	5,261	2,943	2,879	5,822	1,946	4,752	6,698	1,912	3,750	5,662
Gillespie	4,242	1,457	5,699	5,112	721	5,833	5,729	946	6,675	5,985	1,097	7,082
Llano	1,958	3,629	5,587	1,918	3,666	5,584	2,122	3,398	5,520	1,828	2,490	4,318
McCulloch	7,515	780	8,295	7,548	230	7,778	6,060	143	6,203	5,719	229	5,948
Mason	16,861	969	17,830	17,423	833	18,256	18,077	1,381	19,458	13,561	751	14,312
San Saba	3,705	9,226	12,931	3,383	11,513	14,896	1,919	6,294	8,213	2,065	3,164	5,229

Municipal use includes reported city and rural water supply pumpage as well as estimates of pumpage for household uses supplied by individual's wells.

Manufacturing is "reported industrial use" from the Board's Industrial Water Use Survey, though Board estimates may be included in some counties.

By far the largest use is irrigation which is estimated by the Board with the cooperation of various county and federal agencies.

Livestock use is a Board estimate based on government agricultural estimates of livestock populations within the counties. Total livestock use is relatively small, but a significant part of it is from surface water sources, mostly small stockponds or earth tanks.

Table 17 shows the reported municipal use for several of the major cities of the area for the years from 1971 to 1993. These use records show almost identical trends as those for population over the same periods as discussed in the section on Historical Population. Table 18 shows the average 1990 reported monthly water use for several of the area cities, with high usage in the summer and low in January and December, as would be expected.

Population Projections

As a part of its planning effort, the Board makes periodic projections of future population within the cities and counties of Texas. The latest projections, which were completed in December, 1994 for inclusion in the 1996 State Water Plan update, will be used in this report. Tables 19 and 20 show the projected population, by decade from 2000 through 2050 for the seven core counties and the major cities of the study area. Several projections were made based on various parameters. The projections used for this study are based on the "most-likely series" with low rainfall and conservation. As can readily be seen from the figure showing county projections, the counties in the east and southeast part of the study area, i.e. Blanco, Burnet, Gillespie, and Llano, are projected to show significant growth during the projected period, while McCulloch, Mason, and San Saba are projected to decline in population throughout the projection period, 2000 - 2050. In the cities, the pattern of growth or decline follows that of the counties, with Johnson City, Burnet, Marble Falls, Fredericksburg, and Llano projected to grow significantly in population; while Brady,. Mason, and San Saba are projected to decline; and Blanco is projected to remain about the same. Over the period, the projected growth rate for Blanco County is estimated to equal 1.8 percent per year; that for Burnet County, 2.0 percent; for Gillespie County, 1.7 percent,; and that for Llano County, 0.7 percent. McCulloch County is projected to lose 0.1 percent per year; Mason county, 0.4 percent; and San Saba County, 0.1 percent. The projected growth is a continuation of trends which have resulted from the proximity of these eastern and southeastern areas to San Antonio and Austin and the suburbanization of areas farther and farther from the cities. Both the movement of retirees and commuters has contributed to this trend.

Projected Water Demands

Most growth demands should continue to be met with ground water, at least within the core counties of the study area. The additional supplies are most likely to come from the Hickory and Ellenburger-San Saba aquifers. Most surface water users will continue to use surface sources, and will probably be able to secure additional water for growth by purchase of existing water rights. Tables 21 and 22 show the projected

Table 17. Yearly municipal water use for selected area cities, 1971-1993

1971-1993 Yearly Municipal Water Use (*in acre-feet*)							
Year	**Brady**	**Fredericksburg**	**Llano**	**Mason**	**San Saba**	**Johnson City**	**Blanco**
1971	1,701.4	1,322.0	714.8	331.2	585.1	133.2	193.7
1972	1,620.9	1,483.5	740.6	369.4	616.3	137.7	190.8
1973	1,423.8	1,281.5	724.7	361.3	504.1	166.8	184.1
1974	1,802.7	1,488.3	795.5	447.4	584.0	140.4	209.1
1975	1,532.9	1,240.7	697.6	382.8	529.6	140.5	160.3
1976	1,623.5	1,265.0	759.1	498.9	527.0	137.2	173.6
1977	2,126.5	1,560.7	814.4	507.0	741.2	182.9	211.0
1978	1,996.4	1,618.1	805.5	487.6	722.6	177.4	227.5
1979	2,039.0	1,714.6	754.2	447.8	715.2	200.4	249.5
1980	2,359.7	1,939.7	877.6	549.1	867.4	190.2	238.7
1981	2,038.5	1,596.1	758.0	476.4	870.3	195.7	214.9
1982	2,065.0	1,835.7	926.4	541.1	928.3	222.6	242.3
1983	1,995.6	1,857.3	869.8	541.0	955.1	220.4	253.8
1984	2,462.1	2,190.0	1,010.0	577.8	901.5	228.9	283.1
1985	2,239.9	2,031.4	906.3	571.3	1,027.6	210.8	240.3
1986	2,066.1	2,083.8	1,131.0	409.8	1,087.8	224.6	265.9
1987	2,107.6	2,108.8	934.5	624.4	1,164.9	239.4	258.2
1988	2,188.5	2,295.8	1,032.3	495.2	1,446.6	274.4	275.9
1989	2,420.4	2,429.2	1,019.0	480.1	1,098.4	292.8	301.9
1990	2,120.6	2,281.6	940.8	556.8	932.5	232.7	241.1
1991	2,101.3	2,152.1	826.2	544.5	566.2	227.9	26,439.0
1882	1,959.0	2,153.1	830.6	579.1	602.5	231.7	263.4
1993	2,262.1	2,264.2	688.2	688.2	675.8	231.7	258.9

Table 18. Monthly distribution of municipal water use for selected area cities

Monthly Municipal Use Distribution for 1990 *(in acre-feet)*					
Month	**Brady**	**Fredericksburg**	**Llano**	**Mason**	**San Saba**
January	143.8	168.7	57.0	31.3	53.9
February	121.5	140.0	47.4	29.5	47.6
March	134.5	145.1	52.6	31.3	41.5
April	150.1	151.9	61.1	38.9	63.3
May	182.3	174.6	96.2	63.3	71.5
June	300.7	253.9	146.2	88.5	104.3
July	259.1	258.8	111.2	71.2	147.5
August	235.7	238.7	115.5	77.4	108.4
September	199.5	240.7	80.6	31.2	112.7
October	152.1	219.3	70.1	29.3	59.7
November	118.1	154.0	49.3	37.3	61.5
December	123.0	136.2	53.6	28.1	59.7

Table 19. County Population Projections , by decade - 1990-2050

Population Projections from 1996 "Consensus Water Plan" "most Likely Growth Scenario"

	County Population									
Year	Blanco	Burnet	Concho	Gillespie	Kimble	Llano	McCulloch	Mason	Menard	San Saba
1990	5,972	22,667	3,044	17,204	4,122	11,631	8,778	3,423	2,252	5,401
2000	7,468	28,055	3,116	20,700	4,011	12,887	8,780	3,343	2,263	5,497
2010	8,998	34,010	3,229	22,730	4,005	13,372	8,783	3,379	2,283	5,470
2020	10,667	43,536	3,344	25,433	4,000	14,538	8,840	3,399	2,321	5,419
2030	11,910	45,936	3,385	27,153	3,865	14,800	8,642	3,394	2,310	5,247
2040	12,549	47,837	3,359	31,367	3,736	15,361	8,470	3,367	2,304	5,144
2050	12,418	49,810	3,543	34,344	3,632	16,745	8,199	3,340	2,301	4,989

Table 20. City population projections, by decade - 1990-2050

	Selected Area Cities Population				
Year	Blanco	Burnet	Fredericksburg	Brady	San Saba
1990	1,238	3,423	6,934	5,946	2,626
2000	1,328	3,960	7,944	5,955	2,682
2010	1,348	5,005	8,577	5,964	2,668
2020	1,341	5,764	9,528	6,020	2,644
2030	1,334	6,419	10,080	5,917	2,560
2040	1,285	6,613	11,596	5,828	2,509

Table 21. Projected water demand - by county and decade - 2000-2050

	Project Water Demand by County *(in acrefeet)*					
County	2000	2010	2020	2030	2040	2050
Blanco	2,115	2,284	2,373	2,456	2,471	2,432
Burnet	7,098	7,764	8,441	9,075	9,315	9,665
Gillespie	7,276	7,574	7,765	7,926	8,439	8,875
Llano	2,925	2,997	3,004	3,018	3,034	3,155
McCulloch	6,862	6,980	6,942	6,880	6,828	6,777
Mason	19,391	19,283	19,997	18,733	18,469	18,221
San Saba	8,684	8,637	8,384	8,153	7,941	7,757

Table 22. Projected water demands - by city and decade 2000-2050

Projected Water Demand by City (in acrefeet)						
City	2000	2010	2020	2030	2040	2050
Blanco	293	284	269	261	245	236
Brady	1,928	1,871	1,827	1,763	1,710	1,678
Burnet	750	886	968	1,057	1,074	1,099
Fredericksburg	2,056	2,114	2,231	2,326	2,637	2,958
Johnson City	286	324	363	398	411	429
Llano	1,060	1,033	1,003	955	974	1,002
Marble Falls	1,243	1,467	1,699	1,906	1,971	2,049
Mason	576	547	520	510	498	491
San Saba	1,253	1,201	1,143	1,095	1,060	1,028

water demands by county and city as estimated for the 1996 Water Plan update. These demands are based on the "most likely series with conservation" as developed by the Board in December, 1994. Since these estimates are based directly by per capita use on the population growth estimates, the rates of change are the same.

Additional development from the Hickory and Ellenburger-San Saba aquifers should be based on sound scientific evaluation of the aquifers in general as well as of existing wells and well fields. The locations of new well or wellfield sites should be based on these evaluations. Exploratory test holes should be drilled and logged at adequate distances from existing centers of high pumpage so as to reduce interference. When good production areas are found new wells should be completed using the procedures outlined above in the Construction of Wells Section. The development of new supplies of water from these aquifers will of course reduce natural discharge from the aquifers to some extent, and thesefore there will be some reduction of the baseflow since part of this new pumpage would be derived from rejected recharge and part from water which might eventually be discharged from seeps and springs downdip. Since a significant part of this outflow an baseflow is reduced by evaporation and transpiration along the watercources, downstream surface-water availability would not be reduced on a one-to-one basis. The quantification of possible reduction of surface-water availability is beyond the scope of this study with the data available.

POSSIBLE AQUIFER MODELING

One of the specific tasks proposed as a part of this study was to evaluate the possibility of constructing an aquifer flow model or models which could be used as a tool in planning and managing the water resources of the area. The usefulness of such a model would depend on how well it could duplicate the flow regimes within each of the aquifers and also the flows between the aquifers and the movement of water through recharge and discharge between the aquifers and surface water streams and reservoirs. Several aquifer flow models have been constructed by students at the University of Texas at Austin, Baylor University, and Texas A&M University at College Station. These are all relatively simplistic and cover relatively small parts of the aquifers in question.

The complexity of the structure that controls the occurrence and movement of ground water within these aquifers makes accurate regional multi-layered aquifer modeling very difficult. In addition, the lack of adequate well data over much of the areal extent of these aquifers and the uncertainty of fault location, offset movement, and extent make any regional model unreliable in predicting accurately the results of estimated future ground-water development and use. The staff of the Board agree that at this time and with current available knowledge and data, the results of such a model for the Paleozoic aquifers in central Texas would not be worth the time, expense, and/or effort which would be needed for its construction.

POSSIBLE GROUND-WATER PROBLEMS

Potential ground-water problems within the study area are those that endanger any aquifers, pollution (from pesticides, nitrates, etc.); water-level declines (within areas of heavy concentrated irrigation pumpage on the outcrop, areas with high-capacity city wells located too close to each other, etc.); and naturally occurring radioactivity, especially in water from the Hickory aquifer.

Pollution or contamination potential is always a problem, especially on the recharge zone of any aquifer. Within much of the study area, the extensive faulting has added additional entry sites for contaminants to get rapidly into the aquifers. Some isolated instances of nitrate pollution have occurred within all of the counties and all of the aquifers in the study area (see Chemical Quality of Ground Water Section). There is always the potential of pesticide contamination especially in irrigation areas and communities on the outcrop of aquifers. Isolated tests of water from wells in such areas have not identified any instances of pesticide contamination. These and other contamination sources (gas, oil, chemical, etc. spills) will continue to be a potential danger, especially considering the many faults crossing the outcrops of the area aquifers.

Samples from several wells producing from the Hickory and Mid-Cambrian aquifers showed gross alpha concentrations in excess of the recommended limit. While other wells completed in the Ellenburger-San Saba, Mid-Cambrian, and Hickory aquifers have produced samples with Radium concentrations in excess of the recommended limit. In addition, some wells producing from the Hickory and Ellenburger-San Saba aquifers have shown Radon gas concentrations over the recommended limit. The source of this radiation is naturally occurring Uranium and Thorium contained within some of the PreCambrian igneous and metamorphic rocks and in some of the Paleozoic shales derived from the older sediments.

Over much of the area, water-level declines are not a significant problem. In a few more-heavily developed areas, however, declines have occurred and there is evidence that the continued or even accelerated use of ground water in some of these areas may make water-level declines a greater problem. The main problem (or potential problem) areas are in the Brady and Fredericksburg well fields and in the areas of concentrated irrigation pumpage on the outcrop of the Hickory Sand. Much of the problem is the result of poor planning in placing high-capacity wells too close together. The resultant drawdowns are often increased by flow interference caused by the fault compartmentilization of the aquifers. Continued excessive water-level declines are a problem because of added pumping head and loss of production, both of which add to the cost of water use.

CONCLUSIONS AND RECOMMENDATIONS

Paleozoic age aquifers which provide much of the water for all uses in the study area are the Hickory, Ellenburger-San Saba, Marble Falls, and Mid-Cambrian aquifers. The Hickory and Ellenburger-San Saba are much more extensive and important than the other two. Around the edges of the study area, especially in the southwestern and eastern parts, the Edwards-Trinity (Plateau) and the Trinity aquifers overlie the Paleozoic aquifers and provide significant amounts of water, especially for rural domestic and livestock use. Other small but locally important amounts of ground water are produced from isolated thin alluvial deposits along the major streams, and from shallow zones of fracture porosity in the igneous and metamorphic rocks of the central part of the area.

Some significant water-level declines have occurred in areas of heavy pumpage, but in general, most wells show relatively steady levels with changes probably more in response to variation in recharge than to pumping.

Board estimates of ground water available from the Paleozoic aquifers are based on annual effective recharge and include 34,912 acrefeet for the Ellenburger-San Saba, 46,149 acrefeet for the Hickory, 26,400 acrefeet for the Marble Falls, and 1,260 acrefeet for the Mid-Cambrian aquifers.

Both ground and surface water are important to the economy of the study area. Surface water supplies a large part of the demands of several area cities, including Llano, Burnet, and Marble Falls. Surface water is also used for power generation and as a part of the supply for livestock and irrigation. The greatest part of the demand is supplied from ground- water sources, and irrigation is by far the highest use. For the seven core counties (Blanco, Burnet, Gillespie, Llano, McCulloch, Mason, and San Saba) ground water supplied 65 percent of the total demand in 1980, 66 percent in 1985, 68 percent in 1990, and 73 percent in 1992.

While models of some relatively small areas, especially on the outcrop of the Hickory, where adequate data is available and structure is relatively simple, can be constructed and used for specific interpretations and evaluations, a model of the entire area or any appreciable part is impractical to construct. The complex structure of the geologic framework and the relative scarcity of structural data points would make it impossible to construct a model which would replicate the internal working of the aquifer and allow adequate simulation of future pumping schemes, at least at this time.

While only small additional amounts of surface water can be developed in the area or taken from streams, some additional water rights may be secured by purchase of existing irrigation and/or industrial rights. Most of the area should expect to continue to use ground-water supplies from the Paleozoic aquifers for future growth. Of course the development of additional amounts of ground water may cause some significant reductions of downstream availabillity of surface water.

Aggressive programs of water conservation should be implemented throughout the area, especially in public and irrigation use.

Faulting compartmentalizes aquifers in the study area, especially at and near the outcrop. This prevents or restricts flows laterally in many areas. Therefore, pumpage within a compartmentalized area often results in more severe water-level declines within the compartment while effects outside of the compartmentalized area are reduced. In addition, recharge flow into downdip parts of the aquifers can be slowed or restricted. Also, considerable recharge is rejected along some of these faults.

The recommended upper limit of nitrate concentration (MCL) is exceeded in isolated wells completed in the Marble Falls, Ellenburger-San Saba, Mid-Cambrian, and Hickory aquifers in almost all counties of the study area. This is also true of some Trinity and Edwards-Trinity (Plateau) wells. In a few areas, relatively scarce data indicates that this problem may be more general. The most obvious of these is in western Gillespie County in relatively shallow wells completed in the Edwards-Trinity (Plateau) aquifer.

The recommended upper limit (MCL) of radium-226 and radium-228 concentration combined is exceeded in isolated wells completed in the Ellenburger Group, Ellenburger-San Saba aquifer, the Welge Sandstone Member, Mid-Cambrian aquifer and the Hickory aquifer.

Cech et al (1988) found potentially problematic levels of radon-222 in some of 15 samples taken from the Ellenburger-San Saba aquifer and the Hickory aquifer.

The HCUGWCD has tentative plans for implementing artificial recharge through the use of injection and recovery wells in the Hickory aquifer. Careful study of the immediate area of such a project is needed, especially location and mapping of any faults which might reduce the effectiveness by allowing the recharged water to escape back to the surface. Such faults might also severely limit the effective area of recharge.

The HUGWCD and HCUGWCD have expanded water-level and water-quality monitoring within their areas. This should also be done within the extent of the Paleozoic aquifers outside of the districts. If possible, some downdip observation wells might be constructed to gather data in areas where it is lacking. The districts should also continue to encourage graduate students in geology and hydrology to conduct geohydrologic studies on the Paleozoic aquifers and their *interac*tions.

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APPENDICES

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Aluminum (A1)	Aluminum, the most abundant metallic element, is the third most abundant element in crustal rocks. Aluminum makes up about eight percent of crustal rocks and is dissolved mainly from silicate igneous rocks and from sedimentary rocks consisting predominantly of sandstones and shales. Some of the many minerals having significant amounts of aluminum are bauxite, spinels, feldspars, and corundum. Industrial Uses and Sources: Manufacture and production of building materials, various types of vehicles, cans, bottle tops, foils, frozen food trays, light bulbs, power lines, telephone wires, and many other products. Because of its great abundance, aluminum is present in practically all ground waters and surface waters. The predominant form of aluminum in waters having a pH of less than 4.0 is the metallic aluminum cation (Al +3). At pH of about 4.5 to 6.5 a process of polymerization occurs and various simple to complex forms of aluminum hydroxide, $Al(OH)_2$, polymeric ions are present in solution. At pH of 7.0 or greater the predominant dissolved form of aluminum in solution is the anion $A1(OH)_4$ -1 (another form of aluminum hydroxide). The latter anion occurs usually in relatively small concentrations of 1.0 mg/l or less in most natural waters with ground waters having lesser concentrations than surface waters. Water having a pH of 4.0 or less may have several hundred or several thousand mg/l of aluminum (Al +3 cation) which usually occur in some springs and in acidic drainage waters from mining operations.	Aluminum appears to be an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.3 mg/day which is one (1) percent of the average daily intake of 30 mg/day from food, water and air. However, excessive concentrations may be associated with the cause of neurological disorders; namely Alzheimer's disease (encephalopathies), and mental deterioration due to kidney malfunction (dialysis dementia). Excessive concentrations may also cause adult rickets (osteomalacia) by competing with calcium to leave bones soft and susceptible to fracturing. Aluminum is absorbed gastrointestinally, and about 4 percent of intake by humans is retained causing an accumulation with age. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Antimony (Sb)	Antimony, a non-metallic element with chemical traits similar to arsenic, is relatively rare in crustal rocks. It is most abundant in areas of geothermal geysers and in antimonial lead ores. The most important antimonial mineral, is stibnite. Antimony trioxide (Sb_2O_3) is soluble in water while antimony trichloride ($SbCl_3$) is not. The ionic forms of antimony found in water are $2Sb(OH)_2$ +1 cation, $2Sb(OH)_4$ -1 anion, and $2Sb\ (OH)_6$ +3 cation. Industrial Uses and Sources: Manufacture and production of hard and strong lead alloys used in electric cables, batteries, and type printing; compounds of antimony are used in the production of plastics, refrigerators, air conditioners, and aerosol sprays. Surface water may have concentrations of about 0.0004 mg/l while drinking waters have about 0.014 mg/l. Some mine drainage waters may have concentrations of 3 to 6 mg/l.	Antimony is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.024 mg/day which is about 3.3 percent of the average daily intake of 0.725 mg/day from food, water and air. Antimony is not considered to be cancer causing. However, excessive concentrations can be toxic to the gastrointestinal tract, heart, respiratory tract, skin and liver. The most adverse impact is on the heart. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Arsenic (As)	Arsenic, a non-metallic element, occurs naturally in relatively small amounts in sulfide ore deposits, commonly forming metal arsenides. The most important arsenic mineral is arsenopyrite. When dissolved in water, its stable ionic forms are arsenate (As +5) and arsenite (As+3) oxyanions. From pH of 3 to 7, the dominant anion is H_2As_4 -1. From pH 7 to 11, the dominant anion is $HAsO_4$ -2. The uncharged ion $HAsO_2$ (aqueous) occurs under mildly reducing conditions. Industrial Uses and Sources: Manufacture and production of pesticides, paint pigments, leather, glass, ceramics and metals. The dissolved concentration level of arsenic in natural waters rarely exceeds 0.05 mg/l. Concentrations as high as 5 mg/l have been reported in areas where rocks contain gold ores. A concentration of 40 mg/l has been reported in geothermal waters. Concentrations as high as 362 mg/l have been detected in wastewater effluent from manufacture of some pesticides.	Arsenic is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.003 mg/day which is about 4.6 percent of the average daily intake of 0.065 mg/day from food, water and air. Excessive concentrations of arsenic are poisonous and can cause death, with toxicity varying with form of occurrence. Excessive concentrations can also cause body weight changes, and a decrease in blood hemoglobin as well as promote liver and kidney damage. Primary drinking water standard MCL is 0.05 mg/l. Method of Removal: As +3 and As +6 (if present) by reverse osmosis or distillation; As +5 by ion exchange, activated alumina, adsorption, reverse osmosis, or distillation; and organic arsenic complexes by activated carbon.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Barium (Ba)	Barium, an alkaline-earth metallic element, is the sixteenth most abundant element in crustal rocks. It is one of the principal elements in barite ($BaSO_4$), a common mineral that occurs in metallic ore veins and in calcite veins in some limestones. Barium is also widely distributed in soils, especially in the western and midwestern U. S. The ionic form of barium in water is the cation Ba +2. Industrial Uses and Sources: Manufacture and production of drilling muds, paint pigments, ceramics, glass, motor oil, detergents and magnets, and is used to purify chemical solutions and as an indicator in x-ray analyses. Median concentrations of barium in most natural waters is approximately 0.045 mg/l, indicating the relatively low solubility of barite in water. High concentrations can be expected in certain oil-field and other brines.	Barium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.083 mg/day which is 10 percent of the average daily intake of about 0.830 mg/day from food, water and air. Its distribution is primarily to bones, and some studies have linked it to elevated blood pressure. Barium is known to contribute to the hardness of water (see hardness as $CaCO_3$). Primary drinking water standard MCL is 2.0 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Beryllium (Be)	Beryllium, a relatively rare alkaline-earth metallic element, occurs most commonly in beryl and bertrandite which are minerals often associated with pegmatites. The ionic forms of beryllium in equilibrium at pH 6.0 are Be +2 cation, BeOH +1 cation, $Be(OH)_2$ (aqueous) and $Be(OH)_3$ -1 anion. At pH of about 8.5, the Be +2 cation occurs. Industrial Uses and Sources: Manufacture and production of alloys, glass lenses, X-ray tubes, and fluorescent lamps, as a refractory in metal smelting and also as an absorber and conductor of heat in satellites, missiles, rockets and laser technology. Concentrations of beryllium in water are usually very small and usually less than the detection limit of 0.003 mg/l, owing to its low equilibrium solubilities. Concentrations of 1.0 mg/l or more may be regularly detected in acidic (low pH) waters associated with some mining operations.	Beryllium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.001 mg/day which is 8.3 percent of the average daily intake of about 0.012 mg/day from food, water and air. Its adverse effects on humans are unclear. However, some studies have linked it with decreases in growth rate. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Boron (B)	Boron, a non-metallic element, is relatively rare in crustal rocks, but is widely distributed as orthoboric acid (H_3BO_3 and H_2BO_3-1 anion) in volcanic regions, and in evaporites (borates) in some arid lake regions. The most important boron compound is borax which is from the minerals colemanite and kernite which are readily obtained from brine lakes in southern California. Industrial Uses and Sources: Wood and fabric processing; and manufacture and production of detergents, glassware, leather, carpets, cosmetics, photographic supplies, water softeners and rocket and jet fuels. Boron is a minor constituent of most natural waters with concentrations up to only a few tenths of a mg/l. It is found in oil-field brines and the remains of some plants and animals. High concentrations are found in thermal springs in some volcanic areas where concentrations of 48 to 660 mg/l have been detected. Ocean water has a concentration of about 4.6 mg/l. Relatively high concentrations may be present in sewage and industrial waste effluent.	Boron in proper form and concentrations may be vital to human calcium metabolism (see calcium) to help prevent bone deterioration (osteoporosis), and vital to human copper metabolism (see copper) to help main a healthy cardiovascular system. Appropriate daily boron intake by humans has been reported to range from 1 to 3 mg/day from food, water and supplements. The specific intake limit from drinking water is unknown. Excessive amounts greater than 3 mg/day taken orally from food, water and supplements may be dangerous; adversely effecting human calcium and copper metabolisms. Another investigation of boron indicated that under conditions of low dietary magnesium, dietary boron may influence the brain function of healthy adult men and women. Boron in small concentrations is essential for plant growth. However, high excessive concentrations in soils and irrigation waters are harmful to plants; depending on the type of plant and the concentration of boron. Concentrations as high as 1.0 mg/l are permissible for irrigation of sensitive crops such as fruit trees (lemon, orange, peach, etc.), nut trees (pecans, etc.) and navy beans. Concentrations as high as 2.0 mg/l are permissible on semi-tolerant crops such as most grains, cotton, potatoes, and some other vegetables. Concentrations as high as 3.0 mg/l are permissible on tolerant crops such as alfalfa, and most root vegetables. The most serious hazard posed by boron to the environment (air and perhaps water) is through boranes which are highly toxic compounds used as fuels for rocket motors and jet engines. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Bromide (Br)	Bromine, a relatively rare non-metallic, halogen group element, is similar in chemical behavior to chlorine and in natural waters is always present as the bromide anion Br -1. Its main sources are from sodium, potassium and magnesium bromide salts found in sedimentary rocks such as evaporites, carbonates and shales. Industrial Uses and Sources: Manufacture and production of ethylene dibromide (a gasoline additive), fumigants, fire-retardant agents, pesticides and medicines. Concentrations in most natural waters range from about 0.005 to 0.15 mg/l. Geothermal waters may have concentrations greater than 20 mg/l. Concentrations of up to 3,720 mg/l are found in some brines.	The beneficial or hazardous significance of bromide concentrations in waters used for drinking, industrial or irrigation purposes is unknown. The presence of small amounts of bromide in fresh water probably is not of any ecologic significance. The introduction of bromine to the environment by human activities in urban areas is probably significant. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Cadmium (Cd)	Cadmium, which is chemically similar to zinc, is a relatively rare metallic element, and occurs in the mineral greenockite and as a secondary constituent in zinc ores such as sphalerite and some copper ores. The simple ionic forms found in ground waters are the Cd +2 cation at pH less than 8.0, and Cd (OH) (aqueous) and the Cd $(OH)_3$ -1 anion at high pH. Industrial Uses and Sources: Electroplating and manufacture and production of pigments, printing ink, plastics and batteries. Cadmium is relatively insoluble in water, rarely occurring in concentrations over 0.01 mg/l. Excessive concentrations may be detected in acidic (low pH) waters associated with some mining operations.	Cadmium is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.001 mg/day which is 2.9 percent of the average daily intake of 0.035 mg/day from food, water and air. Excessive concentrations in water accumulate in the kidney and liver and may cause kidney damage and abnormal presence of protein, sugar and amino acid in the urine. Cadmium is also known to cause lung and prostate cancer when inhaled. Primary drinking water standard MCL is 5.0 µg/l. This concentration is also the upper limit for irrigation waters, because cadmium is known to accumulate in and be toxic to plants. Method of Removal: Distillation, reverse osmosis or ion exchange.
Calcium (Ca) and Magnesium (Mg)	Calcium and magnesium are alkaline-earth metallic elements and are readily dissolved from practically all soils and rocks. Calcium, the fifth most abundant element in crustal rocks, makes-up about 3.5 percent of crustal rocks and is the most abundant alkaline-earth metallic element. It is mostly derived from such minerals as amphiboles, feldspars, gypsum, pyroxene, aragonite, calcite, dolomite and clay minerals. The ionic forms of calcium are the cations Ca +2 and $CaHCO_3$+1. Magnesium, the eighth most abundant element in crustal rocks, is derived from such minerals as a amphiboles, olivine, pyroxenes, dolomite, magnetite and clay minerals. Magnesium occurs in solutions as the cation Mg +2, but readily precipitates as the mineral brucite, $Mg(OH)_2$. Industrial Uses and Sources: Calcium is used in the manufacture and production of alloys, leather, petroleum, cement, plaster, fertilizers and paint; while magnesium is used for the manufacture and production of alloys, aircraft and automobile parts, tools and other equipment, anodes, fireworks, flares, incendiary bombs, medicines, and protective coatings. Calcium and sodium are usually the dominant cations in natural waters. Magnesium is not a dominant cation in most natural waters because its chemical behavior is very different from that of calcium and sodium. Consequently, in most natural waters, the magnesium concentration is much lower than the calcium or sodium. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water with concentrations exceeding 1,000 mg/l.	Calcium and magnesium are essential elements for human metabolic needs and for plant nutrition. Drinking waters account for about 25 percent of the average daily intake of calcium by an adult human and for about 3 percent of the average daily intake of magnesium by an adult human. A deficiency of calcium may result in bone deterioration (osteoporosis) while an excess may cause kidney stones. A deficiency of magnesium may result in an electrolyte imbalance, while an excess may cause muscle weakness. High concentrations of magnesium have a laxative effect, especially on new users of the water supply. Calcium and magnesium combine with carbonate, bicarbonate, sulfate, and silica to form heat-retarding, pipe-clogging scale in boilers, water heaters, cooking utensils, and other hot water using appliances and heating utensils, and other hot, water using appliances and heating exchange equipment. Calcium and magnesium are soap consuming (see hardness as $CaCO_3$). Low concentrations are desirable for electroplating, tanning, dyeing, and textile manufacturing. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Carbonate (CO_3) and Bicarbonate (HCO_3)	The carbonate (CO_3 -2) and bicarbonate (HCO_3 -1) anions result from the reaction of carbon dioxide (CO_2) with water and carbonate rocks such as limestone and dolomite. Also the hydrolysis of calcite ($CaCO_3$) with water forms bicarbonate (HCO_3-1). The carbonate and bicarbonate anions and carbon dioxide influence water acidity and alkalinity. Carbonate is usually only present in natural waters when the pH exceeds 8.3. In ground waters, the carbonate concentration is commonly less than 10 mg/l, while the bicarbonate concentration is commonly less than 500 mg/l, but may exceed 1,000 mg/l in water that is highly charged with carbon dioxide (CO_2).	Carbonate and bicarbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, they cause carbonate hardness (see hardness as $CaCO_3$). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Chloride (Cl)	Chlorine, a relatively abundant non-metallic halogen group element, is present in waters as the anion chloride (Cl -1). It is dissolved mainly from the mineral halite (NaCl) or common rock salt found in sedimentary rocks and soils. Chloride is present in sewage and found in large amounts in oil-field brines, sea water and industrial brine effluent. Industrial Uses and Sources: Chlorine is used to purify drinking water, kill bacteria in wastes, and in the manufacture and production of herbicides, pesticides, drugs, dyes, metals and plastic; while chloride compounds are used in photography, preservatives, medical products, electroplating and soldering. Chloride is present in all natural waters. Concentrations are usually low in fresh surface waters and slightly higher in fresh ground waters with concentrations usually less than 300 mg/l. Concentration in sea water is about 19,000 mg/l. Concentration in some brines can be as much as 190,000 mg/l.	Chloride is essential for human metabolic needs. A deficiency may result in increased alkalinity of the blood which may cause hypochloremic alkalosis. Excessive chloride may result in decreased alkalinity of the blood which may cause hyperkalemic metabolic acidosis. Chloride concentrations in excess of 100 mg/l in combination with sodium imparts the salty taste to drinking water. The average daily intake by an adult human from drinking waters is less than 84 mg/day and is less than one (1) percent of the average daily intake of 8,440 mg/day from food, water and air. In large quantities, chloride increases the corrosiveness of water. Food processing industries usually require less than a 250 mg/l concentration. Secondary drinking water standard MCL is 300 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Chromium (Cr)	Chromium, a relatively rare transition metallic element, occurs most frequently in nature in ultramafic igneous rocks and in lathyritic soils that overlie ultramafic igneous rocks. The most important chromium mineral is chromite. Dissolved chromium may be present in water as trivalent cations Cr +3, or as anions in which the oxidation state is Cr +6. Industrial Uses and Sources: Manufacture and production of alloys, plated metals, electric heating elements, leather, paint, dyes, anodes and cement. Concentrations of chromium in natural waters are commonly less than 0.01 mg/l. A concentration of 14 mg/l has been detected in ground water contaminated by industrial effluent. Concentrations of 0.1 to 0.2 mg/l have been detected in ground water contained in rocks having chromium minerals.	Chromium is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.016 mg/day which is 13 percent of the average daily intake of 0.12 mg/day from food, water and air. A deficiency of chromium may result in degeneration of blood vessels (atherosclerosis). The toxicity of chromium may include loss of kidney tissue (tubular necrosis). It appears not to be cancer causing. Primary drinking water standard MCL is 0.1 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange; and activated carbon for organic chromium compounds.
Cobalt (Co)	Stable (non-radioactive) cobalt, a relatively rare transition metallic element, is found mostly in igneous rocks and shales, and occurs in such minerals as cobaltite and cobaltomenite which are usually associated with pyrite. Stable cobalt is found in oxide, carbonate, chloride, hydroxide, nitrate and sulfate forms. The common ionic form found in ground water is the Co +2 cation. Stable cobalt also occurs in other complex ionic forms in water. Industrial Uses and Sources: Manufacture and production of alloys for high speed cutting tools and surgical instruments and as a catalyst. Radioactive cobalt is found in 18 isotope forms. In natural waters stable cobalt usually occurs in very low concentrations of less than 0.001 mg/l which usually cannot be detected. Concentration in sea water, is probably about 0.00003 mg/l. Concentration in water within and near mineralized zones has been detected at about 0.02 mg/l.	Stable (non-radioactive) cobalt is an essential element for human metabolic needs. The average daily intake by an adult human for stable cobalt is 3.5 mg/day from food, water, and air. The specific amount from drinking water is unknown. A deficiency of stable cobalt may result in anemia. Excessive oral intake of stable cobalt may adversely impact the nervous system, testes, blood, heart and thyroid. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Copper (Cu)	Copper, a moderately abundant metallic element, occurs in crustal rocks as free native metal, and in such copper minerals as chalcocite, bornite, cuprite, malachite, and azurite. Copper forms rather stable sulfide ore minerals, which also sometimes contain iron. Copper commonly occurs in water as Cu +2 or Cu +1 cation forms. Above pH 7.0, the dominant form may be the anion $Cu(OH)_3$ -1. Aerated water with carbon dioxide may have $CuCO_3$ (aqueous) as the dominant uncharged ion. Industrial Uses and Sources: Manufacture and production of various types of wire, superconductors, electroplating solutions, electronic and electrical parts, chemical etching solutions, pesticides and many other products. Copper may be present in concentrations as great as a few hundred mg/l in acidic (low pH) drainage waters from copper mines. Natural waters usually contain less than 0.01 mg/l.	Copper is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.2 mg/day which is 12 percent of the average daily intake of 1.7 mg/day from food, water and air. A deficiency may result in anemia, loss of pigment in the skin, reduced growth and loss of arterial elasticity. Toxicity may include Wilson's disease (damage to the brain, eyes, kidney, and liver) for susceptible persons, and liver disorder (hepatic cirrhosis). Secondary drinking water standard MCL is 1.0 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Cyanide (CN)	Cyanide is a synthetic organic substance commercially made on a large scale by reacting methane gas (CH_4) with the ammonium cation (NH_4 +1) to form hydrogen cyanide (HCN) which occurs as a liquid at 25.6°C and readily hydrolyzes in water. The ionic form of cyanide is the CN -1 anion which forms stable complex compounds with most metals. Industrial Uses and Sources: Production of methyl methacrylate, acidic acid, nylon, gold from gold ores, and fertilizers. The average concentration in drinking water has been determined to be 0.00009 mg/l.	Cyanide is a non-essential constituent for human metabolic needs. The average daily intake by an adult human has been estimated to be 0.00009 mg/l. Free compounds of cyanide are readily absorbed through the gastrointestinal tract and lung. Cyanide is distributed to the blood, lung, liver and kidney. Excessive concentrations in water may result in hyperventilation, vomiting, unconsciousness, convulsions, rapid and irregular heart rate, vascular collapse and death. EPA's "no observed adverse effect levels" for various cyanide compounds are given on page 237 of Lappenbusch, 1988,, and range from 0.020 mg/l for hydrogen cyanide to 0.200 mg/l for phosphorus-silver cyanide. Method of Removal: Alkaline chlorination, electrolytic decomposition, ozone oxidation or ion exchange.
Fluoride (F)	Fluorine, a moderately abundant non-metallic halogen group element, is present in waters as the anion fluoride (F -1). It is dissolved in small to very small quantities from such minerals as fluorite, amphiboles, apatite, and mica. Fluoride minerals are most commonly found in carbonate rocks, volcanic rocks or sedimentary rocks derived from volcanic rocks. Industrial Uses and Sources: Manufacture and production of glass, steel, aluminum, pesticides, and fertilizers, and in electroplating. Concentrations of fluoride in natural waters generally do not exceed 10 mg/l in ground waters or 1.0 mg/l in surface waters. The concentration of fluoride may be as much as 1,600 mg/l in some brines. Fluoride is added to many public drinking waters by fluoridation.	Fluoride is an essential constituent for human metabolic needs. The estimated average daily intake of fluoride by an adult human is about 1.7 mg/day from food, water, and air. About one-half (0.85 mg/day) of this is probably from drinking waters. Fluoride concentrations between 0.6 and 1.7 mg/l in drinking water have a beneficial effect on the structure and resistance to decay of children's teeth. A deficiency may result in weakening of bone (osteoporosis). Certain but unknown concentrations of unusually high fluoride may be beneficial for the prevention of hardening of the arteries. Excessive fluoride may cause mottling of teeth and abnormal bone thickening and hardening (osteosclerosis) depending on the concentration, age of the individual, amount of water ingested, and susceptibility of the individual. Primary drinking water standard MCL is 4.0 mg/l. Secondary drinking water standard MCL is 2.0 mg/l. Method of Removal: Distillation, reverse osmosis, ion exchange or lime softening.
Gross Alpha	Alpha radiation consists of the emission of positively charged helium nuclei from the nucleus of atoms having high molecular weight. When an alpha particle is emitted from an atom, the atomic weight of the atom decreases by four (4) units. This is called radioactive decay or disintegration and is measured and reported in water analyses as gross alpha in picocuries per liter (pCi/l). Alpha-emitting isotopes in natural waters are mainly isotopes of radium and radon (see radium and radon) which are members of the uranium and thorium disintegration series. Natural waters having high gross alpha concentrations usually occur in deep aquifers or in areas effected by uranium or phosphate mining. Most natural ground waters in Texas probably have gross alpha concentrations of less than 5 pCi/l. Ground waters produced from the Hickory	The release of energy from an atom of a radioactive substance is called ionizing radiation. Alpha particles which are subatomic particles and one of the forms of ionizing radiation are relatively slow-moving, but carry a strong positive charge with energy levels so high that when they collide with an atom or molecule of other substances, they strip away an electron; thus altering or ionizing the substance. Alpha particle radiation cannot penetrate a piece of paper or human skin, but is very dangerous when the radioactive substance emitting them is contained in ingested water and food or in inhaled air. Therefore, alpha particles emitting from radioactive substances ingested or inhaled are most harmful to living tissues of human internal organs by altering or destroying the atoms and molecules of such tissues. The amount of alteration or destruction of the tissues

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Gross Alpha *(continued)*	aquifer in central Texas commonly have gross alpha concentrations greater than 15 pCi/l, and may have very high levels as much as 50 to 75 pCi/l.	depends on where and how long the tissues were exposed to the radiation and the dosage of the radiation. Under these varying circumstances and conditions, the organ having the effected tissue may repair itself of the damage or may develop cancerous cells and tumors. In some instances, certain ionizing radiation is used to advantage by pinpointing certain cancers in human tissue, bombarding them with heavy-ion radiation, destroying them and prolonging life. The primary drinking water standard MCL for gross alpha radiation is 15 pCi/l. Method of Removal: By the methods used to remove the radioactive substance emitting the radiation (see "Method of Removal" for radium, radon, and uranium).
Gross Beta	Beta radiation consists of the emission of high energy electrons or positrons from the nucleus of atoms having high molecular weight. During the production of a beta particle, the neutron of the atom is converted to a proton and an electron is emitted as the beta particle. When a beta particle is emitted from an atom, the atomic number of the atom increases one (1) unit. This beta particle decay or disintegration is measured and reported in water analyses as gross beta in picocuries per liter (pCi/l). Natural beta-emitting isotopes are those in the uranium and thorium disintegration series, and also from potassium-40 and rubidium-87. Strong beta emitting isotopes from nuclear fission which are important in water chemistry are strontium-89, strontium-90, iodine-131, phosphorus-32 and cobalt-60. High gross beta concentrations greater than 50 pCi/l have been detected in ground waters from the Gulf Coast aquifer in southeastern Texas.	The release of energy from an atom of a radioactive substance is called ionizing radiation. Beta particles which are subatomic particles and one of the forms of ionizing radiation are extremely fast-moving electrons (negatively charged) and positrons (positively charged) which have extremely high energy levels. When beta particles collide with an atom or molecule of other substances they alter or ionize the substance. Beta particle radiation is capable of penetrating several millimeters of human skin, and like alpha particle radiation, it can be harmful when emitted inside the human body (see corresponding paragraph or alpha particle radiation). Positrons emitted as beta particles can combine with free electrons to produce gamma ray radiation which has great penetrating power and is capable of passing easily into the human body causing damage to tissue in the process. The primary drinking standard MCL for gross beta radiation is 50 pCi/l;. Method of Removal: By the methods used to remove the radioactive substance emitting the radiation (see "Method of Removal" for radium, radon, and thorium).
Iodide (I) and Idodate (IO_3)	Stable (non-radioactive) iodine, a relatively rare non-metallic halogen group element, is present in water as the iodide anion (I -1) and iodate anion (IO_3 -1). These forms are widely distributed, with their circulation being strongly influenced by plant absorption. Calcium and sodium iodate salts which are known to occur in some caliche-type saltpeter (sodium nitrate) deposits may be important sources of iodine concentrations in some ground waters. Industrial Uses and Sources: Iodine is used in chemical analyses, while iodine compounds are used in making photographic film, antiseptics and as an additive to table salt. Concentrations in natural waters probably rarely exceed 0.04 mg/l, while sea water has about 0.06 mg/l and some brines contain as much as 50 mg/l.	Iodine is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.010 mg/day from food, water and air. A deficiency may result in an enlarged thyroid gland (goiter). However, excessive concentrations may cause goiter and overactivity of the thyroid gland (hypothyroidism). MCL has not been determined. Method of Removal: Activated carbon.
Iron (Fe)	Iron is the second most abundant metallic element in crustal rocks. Iron is present in numerous igneous rock minerals, and is usually reprecipitated quickly after being released by weathering, commonly forming cement in sedimentary rocks. The most important iron ore minerals are hematite, geothite limonite, magnetite and siderite. Industrial Uses and Sources: Production of steel for a wide variety of products related mainly to transportation, shipping, and construction, and iron compounds used to make dyes, inks, disinfectants, paints and polishing powder. The occurrence of iron in water is also commonly influenced by micro-organisms that metabolize it in the biosphere. The most common form of iron in solution in ground water is the ferrous ion (Fe +2 cation). In alkaline waters with pH above 9.5, the anions, Fe(OH) -1, $FeOH_3$ -1 or $HFeO_2$ -2, can exist in significant concentrations. The ionic forms of iron that exist in acidic (low pH) water are the cations Fe +3 (ferric	Iron is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.6 mg/day which is only 3 percent of the average daily intake of 20 mg/day from food, water and air. A deficiency of iron in the body may result in iron deficiency anemia (a hypochromic anemia). Intake of excessive concentrations may cause gastrointestinal irritation. Oral intake of highly excessive concentrations of iron are known to cause iron deposition in the skin and such vital organs as the heart, pancreas, liver and kidney, with serious impairment of their functions (hemochromatosis). Iron is an essential element in the metabolism of plants. More than about 0.3 mg/l of iron in water will stain laundry and utensils reddish-brown, cause unpleasant taste, and favor growth of iron bacteria. More than 0.2 mg/l is objectionable for most industrial uses of the water. Secondary drinking water standard MCL is 0.3 mg/l. Method of Removal: Ion exchange and

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Iron (Fe) *(continued)*	iron), FeOH +2, and Fe(OH)$_2$ +1; the Fe(OH)$_3$ (aqueous), uncharged ion; the rare cation Fe$_2$(OH)$_2$ +1; and the Fe(OH)$_4$ -1 anion. In water, iron can also form complex ions with chloride, fluoride, sulfate and phosphate. Concentrations of iron in most natural waters is usually very small at less than 0.3 mg/l. However in some areas, concentrations of 1.0 to 10 mg/l of iron are common. Ground waters with pH between 6 and 8 may contain as much as 50 mg/l ferrous iron. Some ground waters with very low pH have extremely high concentrations. Ground water movement through rocks containing oxidized iron minerals and organic debris provide favorable sources for iron in ground waters. High iron concentrations in water may be derived from well casings, pipes, pumps, storage tanks, and other cast iron and steel water delivery facilities and equipment.	reverse osmosis for the ferric ion, and distillation and filtration or chlorination and precipitation for the ferrous ion.
Lead (Pb)	Stable (non-radioactive) lead, a relatively rare metallic element, is rather widely dispersed in igneous rocks and sedimentary rocks such as shales and carbonates. The main source is from such minerals as galena, cerussite and anglesite. The principal ionic forms of lead in ground water are the Ph +2 cation and other complex ions of lead hydroxide, lead sulfate and lead carbonate. Industrial Uses and Sources: Manufacture and production of storage batteries, tetraethyl lead (gasoline additive), paints, dyes, and alloys for pipes and tanks, and shields against radiation. The radioactive beta-emitting isotope, lead-210, is produced in the decay series of uranium-238, has a 21.4 year half-life and has been used as a tracer in hydrologic studies. The natural mobility of stable lead is low because of the low solubility of lead hydroxy carbonates; therefore, concentrations in natural waters rarely exceed 0.01 mg/l. Concentrations in rain and snow have been detected at 0.1 mg/l or more in areas having air pollution, and at 0.001 mg/l or more in remote areas. Surface waters sampled in the northeastern and southeastern U.S. had lead concentrations generally greater than 0.001 mg/l while those sampled in the western U. S. had concentrations less than 0.001 mg/l.	Lead is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.015 mg/day which is about 30 percent of the average daily intake of 0.050 mg/day from food, water, and air. Excessive concentrations of lead are known to cause irreversible brain damage when lead concentrations in the blood exceed 100 to 120 micrograms per deciliter. Less severe adverse effects, including physiological disturbances of several organ systems, can be expected at lower excessive levels. Primary drinking water standard MCL is 15.0 µg/l. Method of Removal: Reverse osmosis, distillation or flotation - sedimentation- filtration.
Manganese (Mn)	Manganese is the fourth most abundant metallic element in crustal rocks. Many igneous and metamorphic rocks contain manganese as a minor constituent, and small amounts of manganese are also present in such sedimentary rocks as dolomite and some limestones, substituting for calcium. The main source is from such minerals as franklinite, pyrolusite, manganite and rhodochrosite. In aqueous solution, divalent manganese (Mn +2 cation) commonly precipitates to form coatings of manganese oxide (desert varnish). The ionic forms of manganese in ground water are the cations Mn +2, Mn +3, and Mn +4 with Mn +2 and Mn +4 being the most common. Complex ions of manganese hydroxide and manganese bicarbonate may also be present in waters. Industrial Uses and Sources: Manufacture and production of alloys, batteries, paint, glass, flares and fireworks. Concentrations of manganese in natural waters are usually small, with exceptions above 1.0 mg/l occurring around some thermal springs and in brines.	Manganese is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.086 mg/day which is only 2 percent of the average daily intake of about 4.3 mg/day from food, water, and air. A deficiency may result in decreased enzymatic reactions in carbohydrate metabolism, organic acids. Adverse effects from excessive concentrations may include neuro behavioral changes, anemia and muscle cramps. Secondary drinking water standard MCL is 0.05 mg/l. Method of Removal: Filtration (oxidizing filters), ion exchange, reverse osmosis, distillation or chlorination and precipitation.
Mercury (Hg)	Mercury, a metallic element, and mercury ore (the mineral cinnabar) are rare in crustal rocks and not widely dispersed. The most common ionic form of mercury in ground water is the cation Hg +2. It also can occur as the complex organic cation HgCH$_3$ +1 (methyl mercury). Industrial Uses and Sources: Manufacture and production of organic pesticides, explosives, batteries, photographic	Mercury is a non-essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is only 0.002 mg/day which is about 30 percent of the average daily intake from food, water and air. Any measurable concentration from drinking water is undesirable. Adverse effects from excessive concentrations of mercury may include kidney damage and abnormal

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Mercury (Hg) *(continued)*	supplies, scientific instruments, paints, pharmaceuticals, paper and pulp, and catalysts. Mercury compounds are emitted during the combustion of coal and oil. Concentrations of mercury in natural waters are usually less than 0.002 mg/l, with exceptions occurring near cinnabar mines and around industrial sites where the element is used for various purposes.	presence of protein in the urine. Also, ethyl mercury adversely affects the nervous system. Primary drinking water standard MCL is 0.002 mg/l. Method of Removal: Reverse osmosis or distillation.
Molybdenum (Mo)	Molybdenum is a relatively rare transition metallic element found most commonly in the minerals molybdenite and wulfenite. In oxidizing environments, the dominant ionic form of molybdenum is Mo +6. In waters having a pH greater than 5.0 the dominant form is the anion MoO_4 -2. Industrial Uses and Sources: Manufacture and production of alloys, wire, lubricants, electrical parts, fire proofing fabrics, and in the dyeing of leather, silk and wool. Most natural waters contain less than 0.001 mg/l. Concentrations as much as 3.8 mg/l have been detected in waters effected by molybdenum mining operations.	Molybdenum is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is about 0.011 mg/day which is about 3 percent of the average daily intake of 0.35 mg/day from food, water and air. A deficiency may result in reduced quantities of metallo-enzymes. Adverse effects from excessive concentrations include liver, kidney, spleen, and adrenal damage. At some natural, excessive concentrations, toxicity may include elevated uric acid resulting in gout and bone and joint deformities. MCL has not been determined. Method of Removal: Ion exchange, reverse osmosis or distillation.
Nickel (Ni)	Nickel is a relatively rare transition metallic element in crustal rocks that sometimes substitutes for iron in ferromagnesian igneous-rock minerals, and which tends to precipitate with iron and manganese oxides. Nickel is mined with ferrous sulfide ores and nickel-bearing ores developed on ultramafic bedrock. Important nickel-bearing minerals include niccolite, millerite, pentlandite and garnierite. The ionic forms of nickel in ground water are the cations Ni +2, Ni +3, and Ni +4. Industrial Uses and Sources: Manufacture and production of alloys, scientific instruments, pendulums, steel tapes, coins, electrical parts, propellers, acid pumps, valves and plated metals. A median concentration of 0.01 mg/l is estimated for natural waters. Concentrations of about 0.04 mg/l have been detected in waters in some mineralized regions.	The importance of nickel for human metabolic needs is unknown. The average daily intake by an adult human from drinking waters is not specifically known, but the average daily intake is about 0.34 mg/day from food, water, and air. Toxicity may include gastrointestinal irritation and an inflammation of the skin (dermatitis). Nickel is cancer causing when inhaled but not when ingested. MCL has not been determined. Method of Removal: Ion exchange, reverse osmosis or distillation.
Nitrate (NO_3) or Nitrate as Nitrogen (N)	The main source for the occurrence of nitrogen in ground water are decaying organic matter, human and animal wastes, fertilizers, and the minerals soda niter (sodium nitrate) and niter (potassium nitrate) found in rocks and soils. Nitrogen ionic forms that occur in ground water are the anions NO_3 -2 (nitrate), and NO_2 -2 (nitrite) and the cation NH_4 +1 (ammonium). The nitrate anion (NO_3 -2) is the ionic form most commonly detected in ground water. The nitrite and ammonium ions are generally unstable in ground water and are usually not detectable. Another nitrogen ionic form is the cyanide anion CN -1 (see cyanide) which may be found in ground water contaminated by some wastewater effluents. Concentrations of nitrate in natural waters usually are very small when not influenced by sewage or ranching and farming activities. Some areas with rocks and soils having significant amounts of nitrate minerals, can have associated waters with unusually high natural concentrations of nitrate.	Nitrate is a non-essential constituent for human metabolic needs. The average daily intake by an adult human from drinking waters is about 20 mg/day which is about 13 percent of the average daily intake from food, water and air. Nitrate concentrations in water which are significantly greater than the local average may suggest pollution. Water having excessively high nitrate concentration have been reported to be the cause of methemoglobinemia (an often fatal disease in infants); therefore such water should not be used for infant feeding. Excessive concentrations of nitrate may be a cancer precursor. Nitrate is helpful in reducing intercrystaline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors. Primary drinking water standard for nitrate (NO_3) is 44.3 mg/l. Primary drinking water standard for nitrate as nitrogen (N) is 10 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Phosphate (PO_4)	Phosphorus is a moderately abundant non-metallic element in igneous rocks, occurring in apatite and other phosphate minerals. It is also moderately abundant as phosphate minerals in some limestones, sandstones and shales. Industrial Uses and Sources: Manufacture and production of phosphoric acid detergents, fertilizers, munitions and superphosphate. Phosphate ionic forms in water include H_3PO_4 (aqueous), H_2PO_4 -1, HPO_4 -2, and PO_4-3. The ionic form present is dependent on the pH of the water. The anions H_2PO_4 -1 and HPO_4 -2 are present in ground waters having pH of 5.0 to 9.2. Concentrations of phosphate in natural waters are normally no more than a few tenths	Phosphate is an essential constituent for human metabolic needs, and is used as a nutrient by animals and plants. The average daily intake by an adult human from drinking waters is probably less than 15 mg/day and is less than one (1) percent of the average daily intake of 1,500 mg/day from food, water, and air. A deficiency of phosphate may result in weakness, bone pain and rickets. Adverse effects from excessive concentrations may include gastrointestinal irritation, and kidney and liver damage. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Phosphate (PO_4) *(continued)*	of a mg/l owing to the low solubility of most of its inorganic compounds and its use by biota as a nutrient. Phosphate is a common component of sewage and is always present in animal waste.	
Radium (Ra)	Radium, an alkaline-earth metallic element that behaves chemically somewhat like barium, is strongly radioactive with four naturally occurring isotopes; namely radium-223, radium-224, radium-226, and radium-228. The dominant isotopes found and detected in natural waters are radium-226 which is a disintegration product of uranium-238, and radium-228 which is a disintegration product of thorium-232. This disintegration or radioactive decay is spontaneous and causes radium-226 to disintegrate to radon-222 (see radon) by the release of beta particles. Radium is derived from igneous rocks such as granites, uranium ore bodies, certain shales and sandstones, and volcanic tuffs. The ionic forms of radium are the cation Ra +2 and $RaSO_4$ complex ions. Radium is used in the treatment of cancer and other diseases, as an eluminant, and for the detection of flaws in steel. In water analyses radium concentrations are measured and reported in picocuries per liter (pCi/l). The total radium concentration for most water analyses is the sum of radium-226 and radium-228 in pCi/l. The concentration of total radium in most natural waters is usually less than 1.0 pCi/l. The population-weighted averages of radium-226 and radium-228 in U. S. community water supplies were determined to be 0.5 and 0.6 pCi/l, respectively. EPA determined population-weighted ranges of 0.3 to 0.8 pCi/l for radium-226 and 0.4 to 1.0 pCi/l for radium 228 in community water supplies. Analyses of fresh ground waters produced from the Hickory aquifer around the Llano uplift of central Texas indicate unusually high total radium concentrations that may be three to four times greater than 5.0 pCi/l. Concentration in some brines has been detected as high as 720 pCi/l.	Radium is not known to have any essential function for human metabolic needs. Radium is known to replace calcium in bone. Excessive concentrations of radium in water may cause bone and bone marrow cancers in humans. Primary drinking water standard MCL for total radium (radium-226 plus radium-228) is 5 pCi/l. Method of Removal: Ion exchange, reverse osmosis or oxidation and reduction when associated with removal of iron.
Radon (Rn)	Radon, a strongly radioactive, alpha-emitting noble gas, is a product of the disintegration of radium isotopes 223, 224, and 226. Radon-222 produced from the decay of radium-226 has a 3.8 day half-life and is the only radon isotope of importance in the water environment because the other radon isotopes have very short half-lives of less than a minute. Radon-222 decays through a series of other isotopes to lead-210. In water analyses, radon-222 concentrations are measured and reported in picocuries per liter (pCi/l). The detection of radon-222 is best obtained by immediate analysis, because of its short half-life, and its loss from solution to the atmosphere. Radon commonly occurs in ground waters in areas having significant concentrations of radium in igneous rocks, uranium ore bodies, clastic sedimentary rocks such as certain shales and sandstones, and volcanic tuffs. Investigations have found that ground waters of the Ogallala aquifer in part of the Texas High Plains had radon concentrations of about 100 to 1,000 pCi/l, that the ground waters of the Hickory aquifer around the Llano uplift of central Texas had radon concentrations of less than 100 pCi/l and up to 1,400 pCi/l, and that radon concentrations in the ground waters of the Gulf Coast aquifer in the Houston area ranged from undetectable amounts to as much as 3,300 pCi/l.	Radon-222 is not known to have any essential function for human metabolic needs. Excessive cumulative exposure to radon-222 and its daughter products has been associated strongly with lung cancer and probably emphysema. Radon-222 gas is emitted from parent rocks and ground water within such rocks. Water wells completed in aquifers having concentrations of uranium and radium are probably conveyors of radon gas to the land surface. Also water pumped by such wells can deliver radon gas to dwellings and other enclosed structures. Radon at elevated levels poses greater health risks than any other constituent currently regulated by the Safe Drinking Water Act. The MCL for radon-222 is 300 pCi/l. Method of Removal: Aeration of water and ventilation to the atmosphere.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Selenium (Se)	Selenium is a rare non-metallic element which is widely distributed in sediments in very small amounts and is chemically similar to sulfur. In the presence of iron, selenium is co-precipitated with the mineral pyrite. One selenium mineral, ferroselite, may be associated with uranium ore deposits. Selenium is found in oxidizing solutions as the anions SeO_3 -2, and SeO_4 -2. These anions are unstable and are readily reduced to insoluble selenium SeO_2 and SeO_3 compounds. Industrial Uses and Sources: Manufacture and production of photoelectric cells, television cameras, copying machines, solar batteries and rectifiers, colored glass and ceramics, and hard rubber. Its aqueous mobility is limited by geochemical controls, and its concentration in natural waters rarely exceeds 0.001 mg/l. Concentrations of 1 to 3 mg/l have been detected in shallow ground waters effected by irrigation drainage waters.	Selenium is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.015 mg/day which is 8 percent of the average daily intake of 0.19 mg/day from food, water and air. A deficiency may result in muscle diseases (myopathies) and possible liver damage. Adverse effects from excessive concentrations may include growth inhibition, liver damage, and an inflammation of the skin (dermatitis). Certain plants take-up and accumulate selenium from the soil and may have concentrations which may cause certain diseases in livestock and other grazing animals. Primary drinking water standard MCL is currently 0.05 mg/l and is to be increased to 0.05 mg/l. Method of Removal: Ion exchange, activated aluminum or reverse osmosis for SeO_4 -2, and ion exchange, reverse osmosis or distillation for SeO_3 -2.
Silica (SiO_2)	The non-metallic element silicon is second only to oxygen in abundance in crustal rocks. The chemical bond between silicon and oxygen is very strong and the silicon ion (Si +4) is the right size to fit closely in the center of four closely packed oxygen ions. This SiO_4 -4 tetrahedron is a building block of most minerals in igneous and metamorphic rocks. The term "silica", meaning the oxide SiO_2, is widely used in referring to silicon in natural water, but the actual form is $Si(OH)_4$ or H_4SiO_4, the hydrated ion. The main sources of silica are from silicate rocks which have quartz, chert, feldspars, ferro-magnesium and clay minerals. Silicates make-up about 95 percent of crustal rocks. Industrial Uses and Sources: Silicon is used in the manufacture and production of integrated circuits, transistors, solar cells and other electronic devices; silica is the main ingredient of glass; silicates and silicones are used as grinding and polishing material and in the manufacture and production of rubber, insulators, lubricants and water repellents. Concentrations of silica in natural waters range generally from 1 to 30 mg/l. Concentrations of silica up to 100 mg/l are common in some areas. The median concentration for silica in ground water is about 17 mg/l. Higher values are generally found in ground water and are related to rock type, water temperature and/or pollution.	The beneficial or hazardous significance of silica concentrations in waters used for drinking or irrigation purposes is unknown. Silica in the presence of calcium and magnesium, forms scale in pipes, boilers, and steam turbines that retard heat, and is difficult to remove. Silica inhibits deterioration of zeolite-type water softeners. Silica when added to soft water inhibits the corrosion of iron pipes. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Silver (Ag)	Silver, a rare metallic element, is found mostly in igneous rocks and such sedimentary rocks as shales and carbonates. It can be found as native metallic silver or in such minerals as argneite, proustite, cerargyritye, and several other silver bearing minerals. Silver occurs in ground water as the cations Ag +2 and Ag +1. It may also occur in complex anionic form as $Ag[IO_4(OH)_2]$ -5. Industrial Uses and Sources: Manufacture and production of jewelry, coins, tableware, dental fillings and alloys, and is used mostly for the production of photographic film. As a consequence, it may be concentrated in surface waters and ground waters around industries producing or using photographic film. The average concentration in natural waters is about 0.0003 mg/l.	Silver is a non-essential element for human metabolic needs. Drinking water is believed to contribute about 7 percent of an adult human's average daily intake from food, water and air. Suggested intake should be none. An adverse effect from excessive concentrations of silver may be a permanent dark discoloration of the skin (argyria). Primary drinking water standard MCL is 0.10 mg/l. Method of Removal: Ion exchange, reverse osmosis or distillation.
Sodium (Na) and Potassium (K)	Sodium, an abundant alkaline-earth metallic element, is dissolved from such minerals and rocks as feldspars, clay minerals, halite, and other evaporites. Sodium is the sixth most abundant element in crustal rocks. The ionic forms of sodium in water are the predominant cation Na +1 and such complex ions as $NaCO_3$ -1, $NaHCO_3$ (aqueous) and $NaSO_4$ -1. Industrial Uses and Sources: Production of table salt, and many uses in industry, medicine, agriculture and photography. Potassium is a less abundant alkaline-earth metallic	Sodium and potassium are essential elements for human metabolic needs. The suggested average daily intake by an adult human for sodium is 2,200 mg/day from food, water, and air. The actual average daily intake is 5,656 mg/day with less than one (1) percent contributed by drinking waters. A deficiency of sodium may result in a deficiency in the blood (hyponatremia) and muscle fatigue. Excessive sodium is believed to cause high blood pressure; consequently, a maximum level concentration of 20 mg/l in drinking

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Sodium (Na) and Potassium (K) *(continued)*	element which makes-up about 2.5 percent of crustal rocks and is dissolved from such minerals as carnallite, sylvite, feldspars, mica and clay minerals. The ionic form of potassium in ground water is the cation K+1. The isotope potassium-40 is radioactive. Industrial Uses and Sources: Manufacture and production of alloys for certain nuclear reactors; while potassium compounds are used in making glass, soap, matches, explosives, medicines, and fertilizers. Sodium concentrations are probably less than 60 mg/l in most fresh natural waters, and as high as 1,000 mg/l in some western streams, about 10,000 mg/l in sea water, and 25,000 mg/l in brines. Relatively high concentrations of sodium are found in most industrial waste effluent waters. Potassium concentrations in natural waters are generally less than 10 mg/l, as much as 100 mg/l in hot springs, and as much as 25,000 mg/l in brines.	water is recommended for most persons having high blood pressure. Sodium in combination with chloride, gives a salty taste to water. A high sodium content may limit the use of water for irrigation (see percent sodium, SAR, and RSC). The suggested average daily intake by adult humans for potassium is 3,754 mg/day from food, water and air with less than one (1) percent (38 mg/day) contributed by drinking waters. A deficiency of potassium may result in a deficiency in the blood (hypokalemia) and muscle weakness. The toxicity from excessive potassium may include diarrhea, excess amount in the blood (hyperkalemia) and poisoning of the kidney (nephrotoxicity). Plants require a certain amount of potassium for healthy growth. More than 50 mg/l of sodium and potassium in the presence of suspended matter can cause foaming in steam boilers. MCL for sodium and MCL for potassium have not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Strontium (Sr)	Stable (non-radioactive) strontium is a moderately abundant alkaline-earth metallic element which is similar to calcium but much less soluble. Strontium is dissolved from such minerals as strontianite and celestite which are found mostly in igneous rocks and such sedimentary rocks as shales and carbonates. The ionic form of strontium found in water is the cation Sr+1. Strontium-90 is a radioactive isotope found in fallout from certain nuclear explosions. Industrial Uses and Sources: Manufacture and production of flares, fireworks, medicines, batteries, paints, rubber, glass and is used in the recovery of sugar from sugar beets and molasses. The median content of strontium in most natural waters used for public supplies is about 0.11 mg/l. High strontium concentrations greater than 1 mg/l have been detected in ground waters in Wisconsin, Ohio, Florida, and Texas where celestite and/or strontianite are common minerals in carbonate rocks. The strontium concentration can be very high in some brines.	The beneficial or hazardous significance of strontium concentrations in waters used for drinking, industrial or irrigation purposes is unknown. Strontium is known to contribute to the hardness of water (see hardness as $CaCO_3$). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Sulfate (SO_4)	The chief sources of sulfur, a moderately abundant non-metallic element, are evaporitic sedimentary rocks. In water sulfur occurs in the oxidation state as the sulfate anion SO_4 -1. Industrial Uses and Sources: Production of sulfuric acid and sulfur compounds for manufacturing and production of various chemicals, metals, paper pulp, textiles, fertilizers, explosives, fungicides, insecticides, rubber, shampoos, batteries, photographic film, and medicines. Sulfate is present in sewage and found in large amounts in oil-field brines, sea water, and various industrial wastewaters. Natural waters commonly have concentrations less than 1,000 mg/l. Most fresh drinking waters have less than 300 mg/l of sulfate. Low sulfate concentrations can result from bacterial reduction of sulfate in anaerobic sediments of certain aquifers. Magnesium and sodium sulfates are highly soluble minerals, and water containing these compounds can attain sulfate concentrations in excess of 100,000 mg/l.	Sulfate is a non-essential constituent for human metabolic needs. The average daily intake of sulfur by an adult human from drinking water is about 9.2 mg/day. Any high concentration in drinking water is undesirable. Water containing about 500 mg/l sulfate tastes bitter. Excessively high concentrations of sulfate in water causes inflammation of the stomach and intestines (gastroenteritis), producing such symptoms as diarrhea, abdominal cramps, nausea, vomiting, and fever, especially in infants and children. Secondary drinking water standard MCL is 300 mg/l. Method of Removal: Distillation, reverse osmosis or ion exchange.
Thorium (Th)	Thorium, a radioactive actinide metallic element, may be more abundant than uranium in most types of rocks. It occurs in such minerals as monarite, thorite, thorianite, and thorbastraesite which are found in such igneous rocks as granites and syenites. Industrial Uses and Sources: Production of uranium-233 for nuclear fuels and manufacture of strong alloys and photoelectric cells. Thorium-232 decay products include isotopes of radium, radon and lead (see radium, radon and lead). The water geochemistry of thorium is not well known. In water, thorium occurs only as the tetravalent cation Th +4, and the low solubility of the oxide tends to keep thorium in	Thorium is not known to be an essential element for human metabolic needs. The known impact of thorium in water quality is related to the toxicity from its radioactive disintegration products such as radium-228 (see radium) and its beta particle emissions (see gross beta). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.

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Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Thorium (continued)	its parent minerals. Not much is known about the concentration of thorium in natural waters due to lack of analyses. Expected range of concentrations in fresh water is probably about 0.00001 to 0.001 mg/l.	
Titanium (Ti)	Titanium, a transition metallic element, is one of the most abundant elements in crustal rocks. It is particularly abundant in igneous rocks, and because it is resistant to weathering, it is also abundant and in some clastic sedimentary rocks such as sandstones and shales. It is present in such minerals as rutile, anatase, ilmenite and certain other iron-bearing minerals. Industrial Uses and Sources: Manufacture and production of paint pigment, dyes, ceramics, electrical components, leather dyes, textiles and alloys. It is well known for its resistance to corrosion. Titanium is very insoluble in water, consequently concentrations in natural waters are very low. Only the cation Ti +4 should be expected in nautral waters. Analyses of titanium in some natural waters for public supply had concentrations of less than 0.0015 mg/l. Analyses of acidic (low pH) waters and some brines have detected concentrations of more than 1.0 mg/l.	The beneficial or hazardous significance of titanium concentrations in waters used for drinking, industrial or irrigation purposes is unknown. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Uranium (U)	Uranium, a moderately abundant radioactive actinide metallic element with relatively weak radioactivity, occurs in various igneous, metamorphic and sedimentary rocks. The uranium nuclide is the starting point in a radioactive decay series that ends with the stable isotope, lead-206. The primary uranium-bearing minerals are uraninite, pitchblende, carontite and uranyl nityrate. The ionic forms of uranium found in ground water are the cations UO_2 +1, U +2, and U +4 and the anions $UO_2(CO)_2$-2, $UO_2(OH)_3$ -1 and other complex anionic forms. Industrial Uses and Sources: Used for nuclear power, nuclear weapons, and paint manufacturing; also, uranium is used in medical research as a radiation source, in scientific research to produce various isotopes and for the production of the artificial elements neptunium and plutonium. Most natural waters have concentrations ranging between 0.0001 and 0.01 mg/l. Concentrations of 1.0 mg/l to about 15 mg/l have been detected in natural waters in and near uranium-bearing rocks and ore bodies.	Uranium is not known to be an essential element for human metabolic needs. It can cause various cancers, and is a bone seeking radioactive element much like radium. The critical organ for its toxicity is the kidney. The known impact of uranium in water quality is related to the toxicity from its radioactive disintegration products such as radium-226 (see radium) and its alpha particle emissions (see gross alpha). MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Vanadian (V)	Vanadium, a relatively rare transition metallic element, is found in the minerals patronite, vanadinite and carrotite which occur in certain lead and uranium ore deposits. The dominant ionic forms of vanadium in ground water are V +5 anionic complexes with oxide and hydroxide. Industrial Uses and Sources: Manufacture and production of special steels for locomotive, automobile, and truck cylinders, pistons and bushings, and for high speed tools and die blocks; and also used as a catalyst. Alloys of vanadium are very rust and corrosion resistant. Its aqueous geochemistry is rather complicated, and fairly high solubility can be expected in oxidizing alkaline environments around ore bodies. However, natural waters rarely have concentrations greater than 0.01 mg/l. Concentration of a few tenths of a mg/l have been detected in acidic (low pH) waters from thermal springs.	Vanadium may or may not be an essential element for human metabolic needs. The effect of a deficiency is unknown. Adverse effects from excessive concentrations may include inflammation of the stomach and intestines (gastroenteritis), producing diarrhea, abdominal cramps, nausea, vomiting and fever. MCL has not been determined. Method of Removal: Distillation, reverse osmosis or ion exchange.
Zinc (Zn)	Zinc is a moderately abundant metallic element in crustal rocks, occurring in such minerals as sphalerite, zincite, franklinite, smithsonite, willemite and hemimorphite. The ionic form of zinc in ground water is the cation Zn +2. Industrial Uses and Sources: Used widely in galvanizing, electroplating and metallurgy, and in	Zinc is an essential element for human metabolic needs. The average daily intake by an adult human from drinking waters is 0.39 mg/day which is 3 percent of the average daily intake of 13 mg/day from food, water, and air. A deficiency may result in reduced appetite and growth. Adverse effects from excessive

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters	Significance, Maximum Contaminant Level (MCL) and Method of Removal
Zinc (Zn) *(continued)*	the manufacture and production of paints, rubber, cosmetics, plastics, soap, paper, and synthetic fibers. Natural waters have a median concentration of 0.02 mg/l. Waters effected by mine drainage commonly contain 0.1 mg/l or more of zinc.	concentrations may include irritability, muscle stiffness and pain, loss of appetite, and nausea. Secondary drinking water standard MCL is 5.0 mg/l. Method of Removal: Reverse osmosis, distillation, or ion exchange.
Dissolved Solids	Dissolved solids (DS) are the approximate total amount of mineral constituents dissolved in water. The measured DS concentration is used in Texas to classify waters according to various degrees of salinity. Waters containing 1,000 mg/l or less DS are considered fresh; those containing 1,001 to 3,000 mg/l DS are slightly saline; those containing 3,001 to 10,000 mg/l DS are moderately saline; those containing 10,001 to 35,000 mg/l DS are very saline; and those with more than 35,000 mg/l DS are brines. Usable waters commonly contain 3,000 mg/l DS or less. Some brines contain as much as 300,000 mg/l DS.	The Texas Department of Health (1988) secondary drinking water standard MCL is 1,000 mg/l for dissolved solids. It is recommended that waters having dissolved solids concentrations exceeding this MCL not be used for drinking purposes, if other less mineralized water supplies are available. For many purposes, the dissolved-solids concentration is a major limitation on water use. Method of Removal: Distillation, ion exchange or reverse osmosis.
Hardness as ($CaCO_3$)	Hardness of water is caused principally by calcium and magnesium ions, but barium and strontium, free acid ions, and heavy-metal ions contribute to hardness also. Hardness as $CaCO_3$ is equal to Ca +Mg+Ba+Sr(me/l)x50.05. If Ba and Sr are not measured, the hardness as [$CaCO_3$ (mg/l) x 2.5] + [Mg (mg/l) x 4.1]. Non carbonate hardness (mg/l) equivalent $CaCO_3$ is equal to (me/l hardness - me/l alkalinity) x 50.05. Water with hardness as $CaCO_3$ of 0 to 60 mg/l is considered soft, of 61 to 120 mg/l is considered moderately hard, of 121 to 180 mg/l is considered hard, and of more than 180 mg/l is considered very hard. Most ground waters in Texas are hard to very hard.	Water low in hardness causes corrosion of metallic surfaces. Hard water consumes excessive amounts of soap, and causes the deposit of soap curd on bathtubs. Hard water forms scale in boilers, water heaters, hot water using appliances and pipes. Hardness equivalent to CO_3 and HCO_3 is called carbonate hardness. Any hardness in excess of this is called non-carbonate hardness. A carbonate hardness value of less than 100 mg/l is considered desirable for domestic use. MCL has not been determined. Method of Removal: Distillation, reverse osmosis and ion exchange.
Conductivity or Specific Conductance (micromhos per centimeter at 25°C)	Conductivity is an indicator of the salinity or mineral content of water, and can be used to estimate the dissolved-solids concentration. The approximate dissolved solids of most waters in mg/l is usually about 65 percent of the measured concudtivity of the water. Much higher percentages usually are associated with waters high in sulfate.	Conductivity is a measure of the electrical conductivity of water and varies with the amount of dissolved solids in the water. MCL has not been determined. The conductivity of water is used to determine the salinity hazard of irrigation waters. A conductivity of 2,250 micromhos/cm probably represents the upper limit of salinity that should be considered as being safe for use of the water for supplemental irrigation.
Hydrogen Ion Concentration (pH)	Acids, acid-generating salts, and free carbon dioxide in waters lower the pH. Carbonates, bicarbonates, hydroxides, phosphates, silicates, and borates raise the pH. The pH of most ground water ranges from 6.0 to 9.0.	A pH of 7.0 indicates the neutrality of a solution. Values of pH higher than 7.0 denote increasing alkalinity, while values of pH lower than 7.0 indicate increasing acidity. The pH is a measure of the activity of the hydrogen ions in solution. It may be expressed using hydrogen ion (H +1) concentration rather than the activity. The corrosiveness of water generally increases with decreasing pH. However, excessively alkaline waters with very high pH may also attack metals. Secondary drinking water standard is 7.0 or greater.
Percent Sodium (% Na)	As an indicator of the sodium hazard of irrigation waters. Calculated as follows by using me/l: %Na = Na(100)(Na+K+Mg+Ca)	Percent sodium is the ratio of the sodium ions to total cations times 100. A sodium percentage exceeding 60 percent is a warning of a sodium hazard. Continued irrigation with this type of water will impair the tilth and permeability of the soil.
Sodium Adsorption Ratio (SAR)	An indicator of the sodium hazard of irrigation waters. Calculated as follows using me/l: $SAR = Na/\sqrt{(Ca + Mg/2}$	The SAR is the ratio for soil extracts and irrigation waters used to express the relative activity of sodium ions in exchange reactions with the soil. An SAR of 14 is probably the upper limit for waters that can be safely used for supplemental irrigation.

Abundance, Sources, Form of Occurrence, Concentration, Significance, Maximum Contaminant Level and Method of Removal for Selected Dissolved Chemical Constituents and Related Properties of Water

Chemical Constituent or Property (Chemical Symbol)	**Abundance, Sources, Ionic Form(s) of Occurrence and Concentration in Natural and Other Waters**	**Significance, Maximum Contaminant Level (MCL) and Method of Removal**
Residual Sodium Carbonate (RSC)	An indicator of the sodium hazard of irrigation waters. Calculated as follows using me/l: RSC = $(CO_3+HCO_3) - (Ca+Mg)$ or RSC = 0.02 (Total Alkalinity - Hardness)	As calcium and magnesium precipitates as carbonates in the soil, the relative proportion of sodium in the water is increased. Waters having 1.25 to 2.50 me/l of RSC are probably marginal for irrigation use, and those having greater than 2.50 me/l RSC probably are not suited for irrigation.

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Appendix Ba - Population Projections for Study Area Counties

County	2000	2010	2020	2030	2040	2050
Blanco	7,468	8,998	10,667	11,910	12,549	12,418
Brown	35,189	36,002	36,828	37,065	36,904	36,575
Burnet	28,055	34,010	40,536	45,936	47,834	49,810
Coleman	9,203	9,017	8,877	8,581	8,336	8,051
Concho	3,116	3,229	3,344	3,385	3,359	3,543
Gillespie	20,700	22,730	25,433	27,153	31,367	34,344
Kimble	4,011	4,005	4,000	3,865	3,736	3,632
Lampasas	15,176	16,561	17,639	18,222	18,824	19,832
Llano	12,887	13,372	14,538	14,800	15,361	16,745
McCulloch	8,780	8,783	8,840	8,642	8,470	8,199
Mason	3,343	3,379	3,399	3,394	3,367	3,340
Menard	2,263	2,283	2,321	2,310	2,304	2,301
Mills	4,774	4,888	5,049	5,154	5,200	5,247
San Saba	5,497	5,470	5,419	5,247	5,144	4,989
Travis	744,080	892,047	1,096,329	1,288,441	1,413,420	1,550,521
Williamson	187,154	240,323	303,079	367,597	420,984	469,419

Appendix Bb - Projected Water Demands for Study Area Counties
By Category and County (in acre-feet)

Blanco County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	1,194	1,316	1,437	1,555	1,591	1,572
Manufacturing	0	0	0	0	0	0
Irrigation	458	435	413	392	372	353
Steam Electric Power	0	0	0	0	0	0
Mining	13	9	5	1	0	0
Livestock	670	670	670	670	670	670
Total	**2,335**	**2,430**	**2,525**	**2,618**	**2,633**	**2,595**

Brown County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	7,686	7,505	7,289	7,173	6,967	6,824
Manufacturing	485	524	567	608	660	714
Irrigation	2,643	2,604	2,566	2,528	2,491	2,454
Steam Electric Power	0	0	0	0	0	0
Mining	300	278	196	177	150	134
Livestock	1,332	1,332	1,332	1,332	1,332	1,332
Total	**12,446**	**12,243**	**11,950**	**11,818**	**11,600**	**11,458**

Burnet County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	4,486	5,076	5,696	6,294	6,443	6,649
Manufacturing	1,246	1,377	1,514	1,655	1,800	1,947
Irrigation	295	290	285	280	275	271
Steam Electric Power	0	0	0	0	0	0
Mining	1,013	987	1,006	1,028	1,058	1,091
Livestock	794	794	794	794	794	794
Total	**7,834**	**8,524**	**9,295**	**10,051**	**10,370**	**10,752**

Coleman County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	1,848	1,723	1,601	1,503	1,444	1,392
Manufacturing	1	1	2	2	2	3
Irrigation	988	977	965	954	942	931
Steam Electric Power	0	0	0	0	0	0
Mining	15	16	16	17	17	17
Livestock	1,134	1,134	1,134	1,134	1,134	1,134
Total	**3,986**	**3,851**	**3,718**	**3,610**	**3,539**	**3,477**

Concho County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	700	689	678	675	661	686
Manufacturing	0	0	0	0	0	0
Irrigation	2,582	2,554	2,526	2,498	2,470	2,443
Steam Electric Power	0	0	0	0	0	0
Mining	0	0	0	0	0	0
Livestock	799	799	799	799	799	799
Total	**4,081**	**4,042**	**4,003**	**3,972**	**3,930**	**3,928**

Appendix Bb - Projected Water Demands for Study Area Counties
By Category and County (in acre-feet) - *cont'd.*

Gillespie County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	3,748	3,854	4,051	4,215	4,743	5,193
Manufacturing	502	556	608	657	727	795
Irrigation	1,965	1,931	1,898	1,865	1,833	1,801
Steam Electric Power	0	0	0	0	0	0
Mining	5	3	1	0	0	0
Livestock	1,294	1,294	1,294	1,294	1,294	1,294
Total	7,514	7,638	7,852	8,031	8,597	9,083

Kimble County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	975	943	895	843	804	779
Manufacturing	1,637	1,777	1,849	1,909	2,067	2,229
Irrigation	1,045	1,002	961	922	884	847
Steam Electric Power	0	0	0	0	0	0
Mining	105	100	99	98	100	103
Livestock	470	470	470	470	470	470
Total	**4,232**	**4,292**	**4,274**	**4,242**	**4,325**	**4,428**

Lampasas County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	2,925	2,997	3,004	3,018	3,034	3,155
Manufacturing	114	121	127	131	141	151
Irrigation	178	176	174	172	170	168
Steam Electric Power	0	0	0	0	0	0
Mining	188	175	176	179	183	189
Livestock	984	984	984	984	984	984
Total	**4,389**	**4,453**	**4,465**	**4,484**	**4,512**	**4,647**

Llano County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	2,909	2,864	2,912	2,891	2,946	3,168
Manufacturing	0	0	0	0	0	0
Irrigation	1,103	1,085	1,067	1,049	1,031	1,014
Steam Electric Power	1,000	2,000	2,000	2,000	2,000	2,000
Mining	143	112	99	65	62	95
Livestock	689	689	689	689	689	689
Total	**5,844**	**6,750**	**6,767**	**6,694**	**6,728**	**6,966**

McCulloch County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	2,915	2,821	2,743	2,633	2,542	2,452
Manufacturing	844	903	963	1,027	1,090	1,153
Irrigation	2,033	1,995	1,958	1,922	1,886	1,851
Steam Electric Power	0	0	0	0	0	0
Mining	146	152	158	164	170	176
Livestock	1,024	1,024	1,024	1,024	1,024	1,024
Total	**6,962**	**6,895**	**6,846**	**6,770**	**6,712**	**6,656**

Appendix Bb - Projected Water Demands for Study Area Counties By Category and County (in acre-feet) - *cont'd.*

Mason County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	736	702	667	650	631	321
Manufacturing	0	0	0	0	0	0
Irrigation	17,490	17,237	16,987	16,741	16,499	16,260
Steam Electric Power	0	0	0	0	0	0
Mining	12	8	4	1	0	0
Livestock	1,256	1,256	1,256	1,256	1,256	1,256
Total	**19,494**	**19,203**	**18,914**	**18,648**	**18,386**	**17,837**

Menard County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	422	404	391	378	367	366
Manufacturing	0	0	0	0	0	0
Irrigation	875	855	835	815	796	777
Steam Electric Power	0	0	0	0	0	0
Mining	0	0	0	0	0	0
Livestock	488	488	488	488	488	488
Total	**1,785**	**1,747**	**1,714**	**1,681**	**1,651**	**1,631**

Mills County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	1,268	1,235	1,209	1,212	1,202	1,205
Manufacturing	0	0	0	0	0	0
Irrigation	2,416	2,364	2,312	2,262	2,213	2,165
Power	0	0	0	0	0	0
Mining	0	0	0	0	0	0
Livestock	1,048	1,048	1,048	1,048	1,048	1,048
Total	**4,732**	**4,647**	**4,569**	**4,522**	**4,463**	**4,418**

San Saba County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	1,657	1,578	1,494	1,420	1,367	1,326
Manufacturing	0	0	0	0	0	0
Irrigation	5,549	5,369	5,196	5,028	4,866	4,708
Steam Electric Power	0	0	0	0	0	0
Mining	172	133	124	123	122	126
Livestock	1,200	1,200	1,200	1,200	1,200	1,200
Total	**8,578**	**8,280**	**8,014**	**7,771**	**7,555**	**7,360**

Travis County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	177,018	202,579	239,477	276,997	300,416	327,746
Manufacturing	7,209	8,104	8,743	9,494	10,385	11,600
Irrigation	736	677	622	572	526	484
Steam Electric Power	7,000	7,000	7,000	7,000	7,000	10,000
Mining	4,880	4,746	5,246	5,791	6,407	7,116
Livestock	906	906	906	906	906	906
Total	**197,749**	**224,012**	**261,994**	**300,760**	**325,640**	**357,852**

Appendix Bb - Projected Water Demands for Study Area Counties By Category and County (in acre-feet) - *cont'd.*

Williamson County

Category	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Municipal	35,384	42,956	51,639	61,150	69,108	77,166
Manufacturing	368	398	409	405	443	481
Irrigation	160	160	160	160	160	160
Steam Electric Power	0	0	0	0	0	0
Mining	1,885	1,845	1,896	1,949	2,007	2,068
Livestock	1,314	1,314	1,314	1,314	1,314	1,314
Total	**39,111**	**46,673**	**55,418**	**64,978**	**73,032**	**81,189**